Astroparticle physics

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AstroParticle and Cosmology
Paris

CERN Summer Student Lecture Programme 2012

What is physics?

Oxford dictionary :

Physics, *plural noun* [treated as singular] :
the branch of science concerned with the nature and properties of matter and energy.

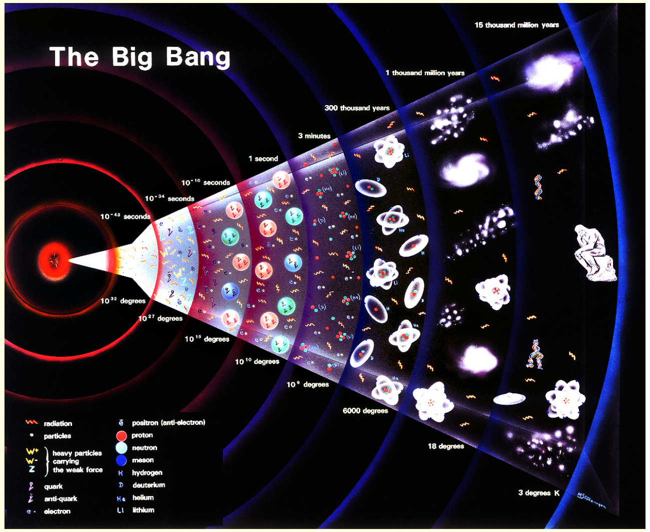
What is particle astrophysics?

Particle astrophysics :
the branch of science concerned with the nature and fundamen-
tal properties of matter and energy in the Universe.

Many different aspects:

• The early Universe a a particle physics laboratory

In the big bang theory, the early
Universe is hot and dense

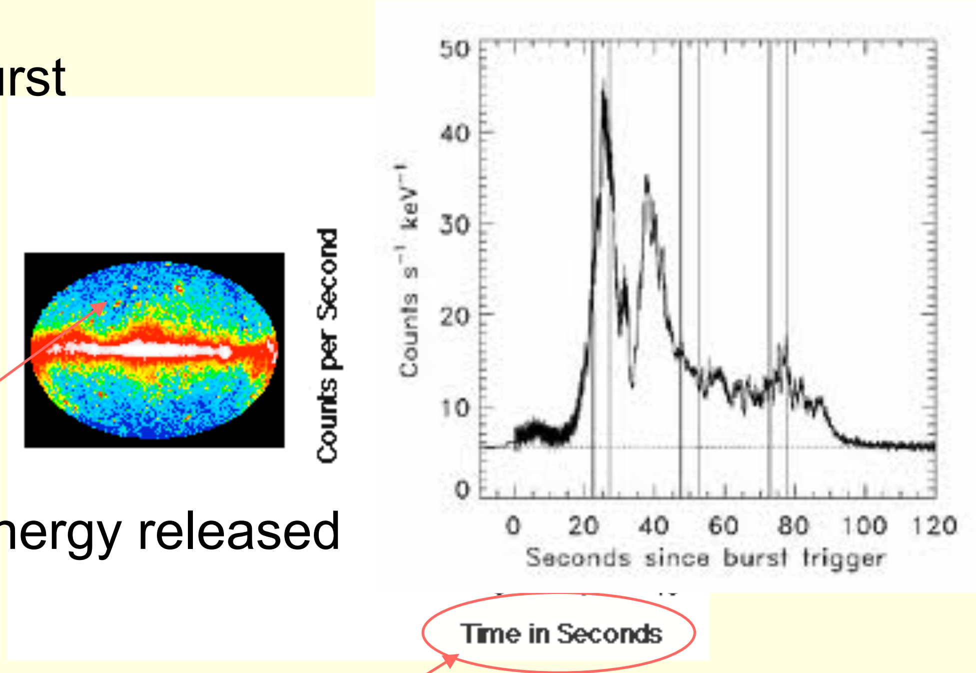


• The matter and energy content of the present Universe: dark and luminous matter, neutrinos, radiation, dark energy…

• Study of violent phenomena in the Universe : particles ejected provide a complementary signal to visible (or electromagnetic) observations

A story of neutron stars, black holes and big bangs…

e.g. gamma ray burst



large amount of energy released

size of the source < 300 000 km

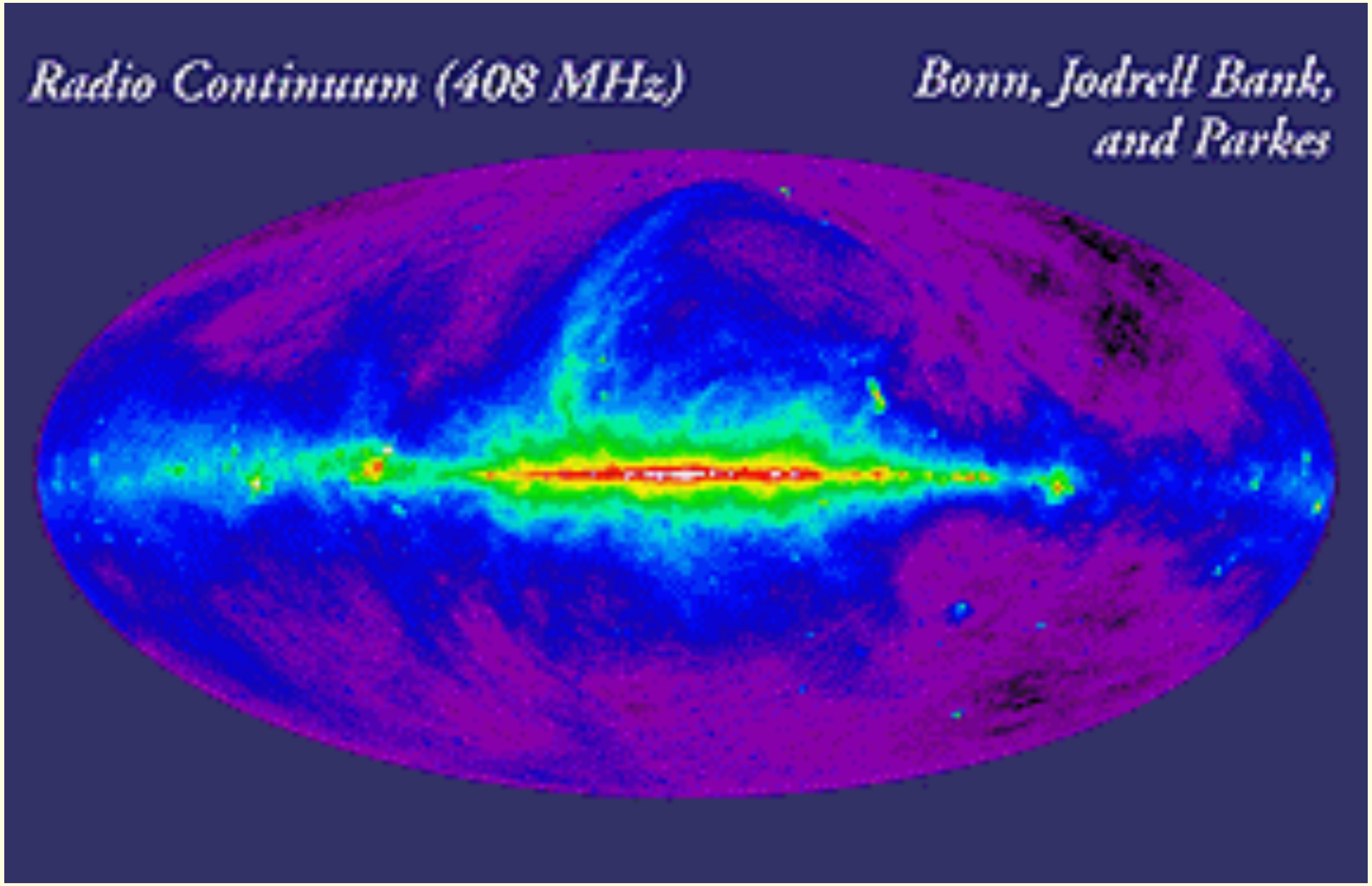
Very compact source of energy !
Best candidates are black holes and neutrons stars.

Astrophysics at the end of XXst century :

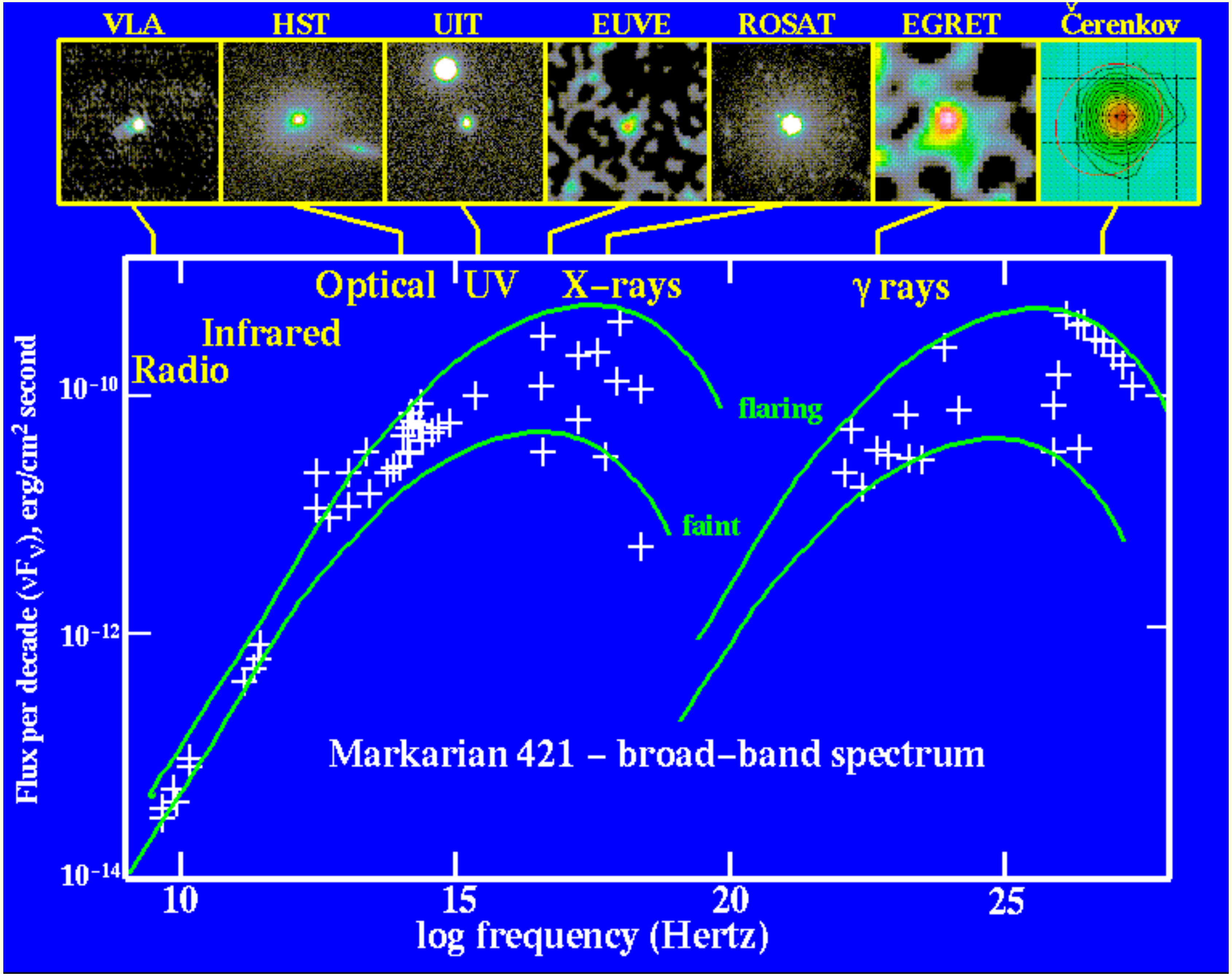
http://adc.gsfc.nasa.gov/mw

The milky way

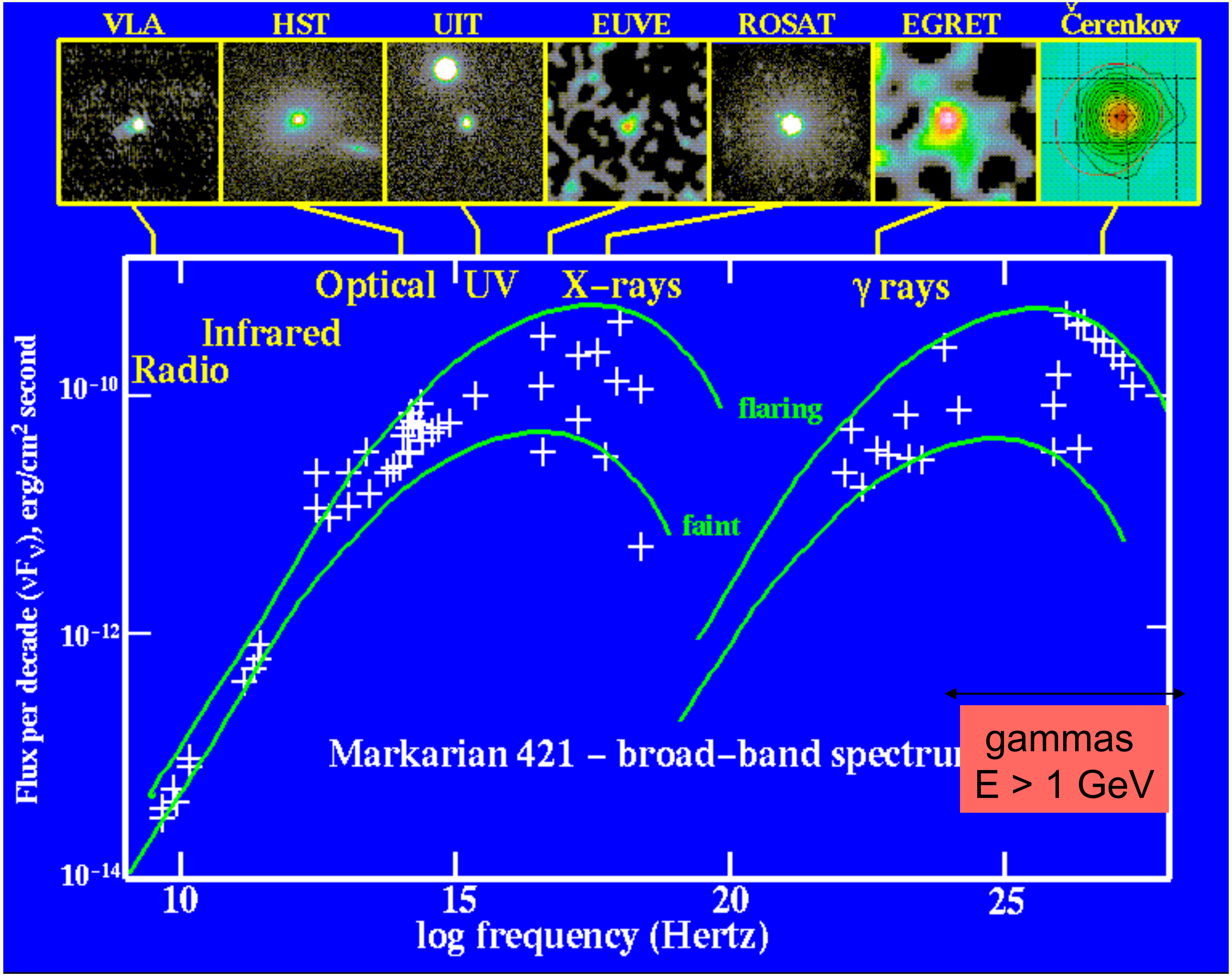
Astrophysics: a multi-wavelength strategy



A multi-wavelength strategy : the Ma 421 source



A multi-wavelength strategy : the Ma 421 source



High energy gammas are one example of astroparticles.

More generally, high energy particles produced in violent cosmic events travel long distances before being deflected by what they encounter: they may help to identify their astrophysical source.

gammas, neutrinos, protons, electrons, ions…

Astroparticles: a multi-messenger strategy

Ideally, one would like to study the same source by detecting the photons, protons, neutrinos and gravitational waves emitted :

- high energy photons trace populations of accelerated particules, as well as dark matter annihilation
- protons provide information on the cosmic accelerators that have produced them
- neutrinos give information on the deepest zones, opaque to photons (e.g. on the origin --hadronic or electromagnetic-- of γ).
- gravitational waves give information on the bulk motion of matter in energetic processes

Outline of these lectures:

Chapter I The tools of the trade

Chapter II The violent universe

Chapter III The Universe at large

Astroparticle physics

I - The tools of the trade

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CERN Summer Student Lecture Programme 2012

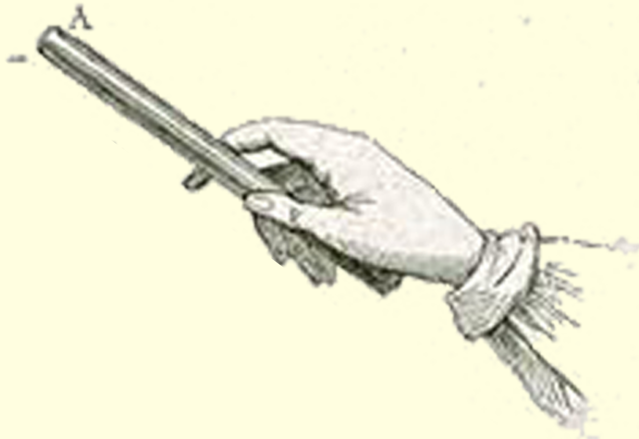
Outline

1. An extraterrestrial radiation
2. The light of particles
3. Detector Earth
4. Ripples of spacetime

1. An extraterrestrial radiation

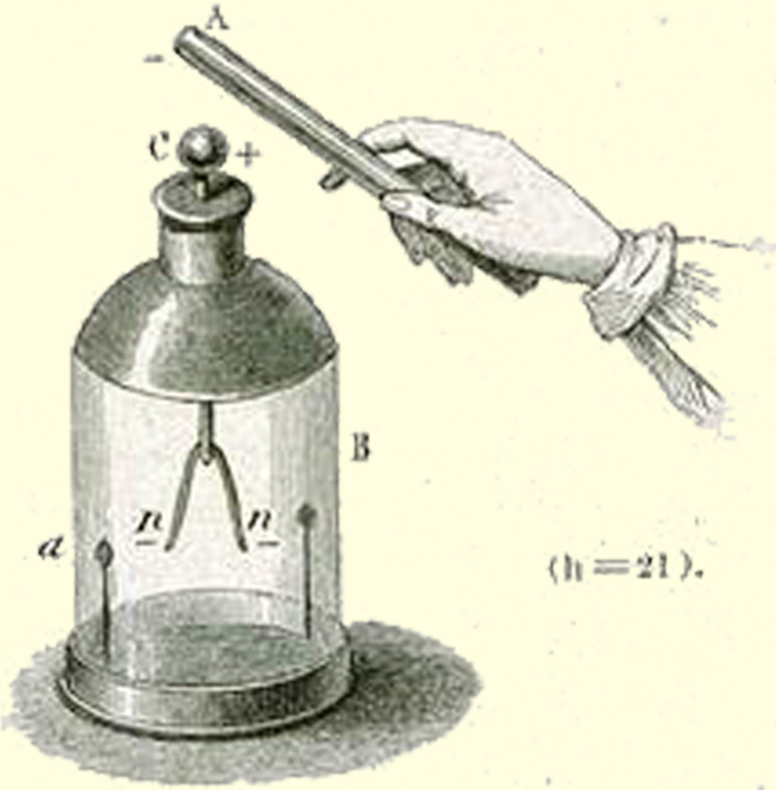
1785

Coulomb



1785

Coulomb



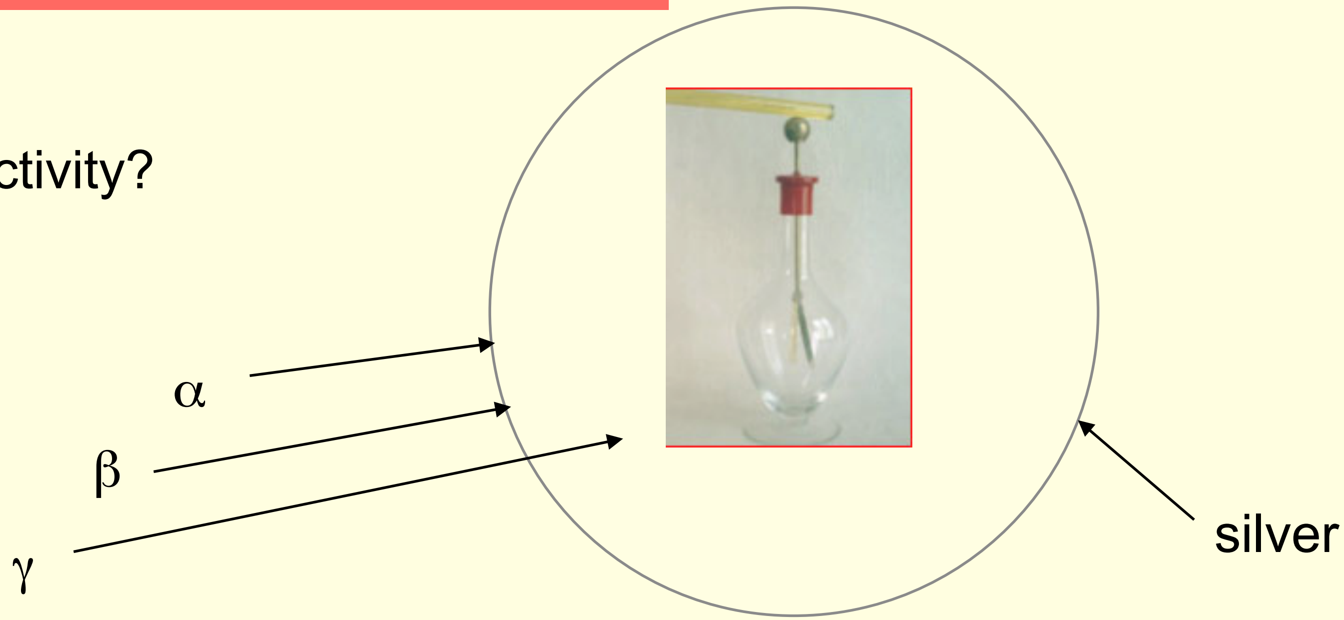
The electrometer discharges with time. Why?

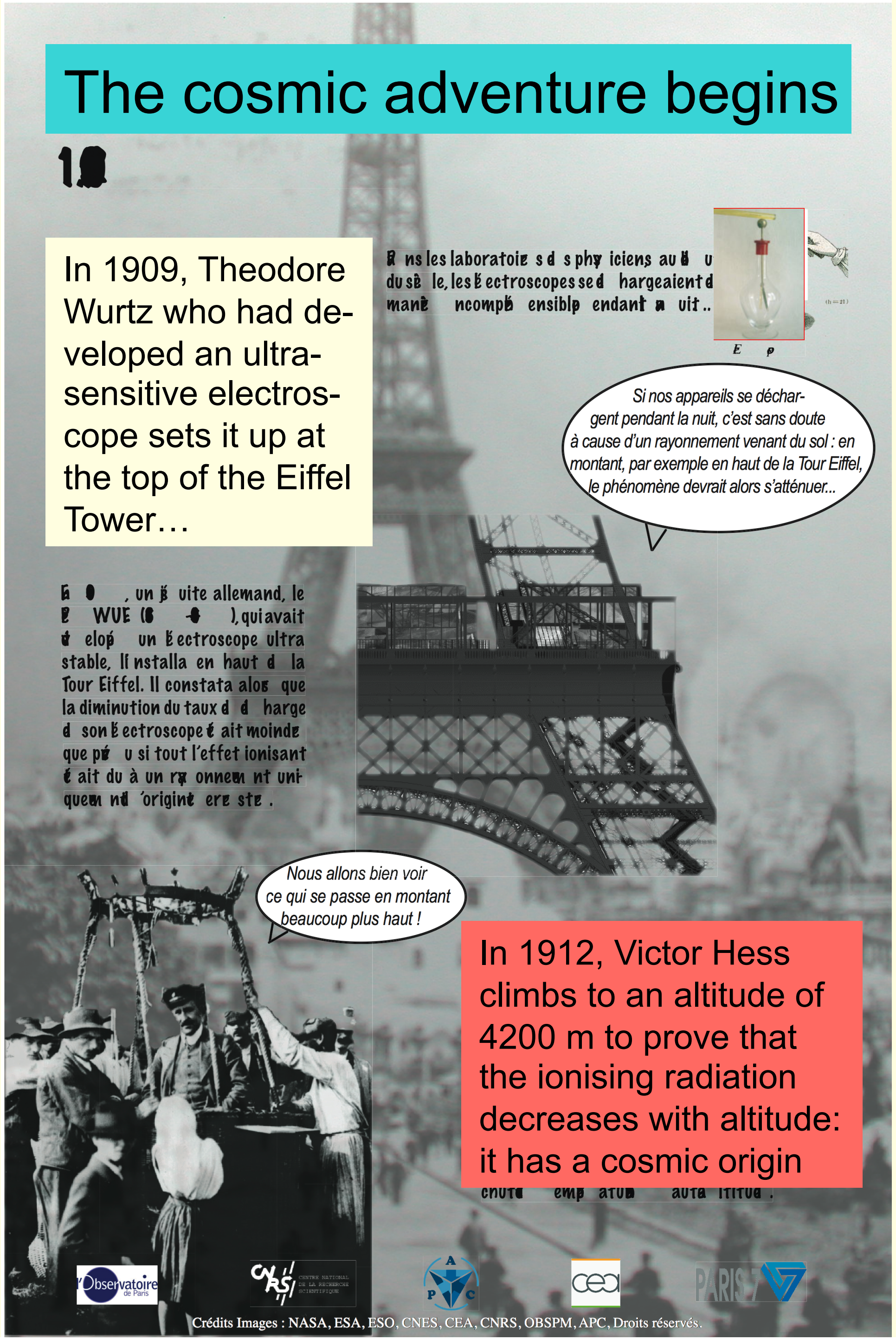
Faraday : the air is a conductor because of ionisation

$$\text{Molecules of air} \xrightarrow{\text{unknown radiation}} \text{Ions}$$

What is the nature of this radiation?

Radioactivity?



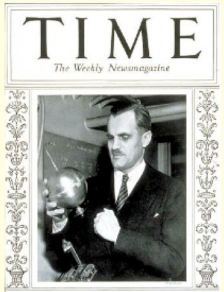


The cosmic adventure begins
In 1909, Theodore Wurtz who had developed an ultra-sensitive electroscope sets it up at the top of the Eiffel Tower…
Si nos appareils se déchargent pendant la nuit, c'est sans doute à cause d'un rayonnement venant du sol : en montant, par exemple en haut de la Tour Eiffel, le phénomène devrait alors s'atténuer...
Nous allons bien voir ce qui se passe en montant beaucoup plus haut !
In 1912, Victor Hess climbs to an altitude of 4200 m to prove that the ionising radiation decreases with altitude: it has a cosmic origin
Crédits Images : NASA, ESA, ESO, CNES, CEA, CNRS, OBSPM, APC, Droits réservés.

Millikan calls this radiation cosmic rays

Cosmic rays are neutral (gamma rays). This is why they are so penetrating

1868-1953



1892-1962

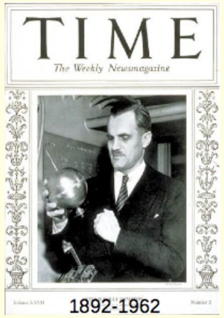
Cosmic rays are charged. This why they are so energetic. They can be accelerated by cosmic magnetic fields

Millikan - Compton controversy

Millikan calls this radiation cosmic rays

Cosmic rays are neutral (gamma rays). This is why they are so penetrating

1868-1953



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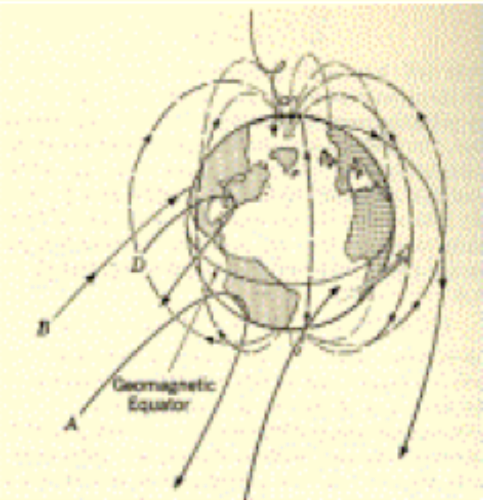
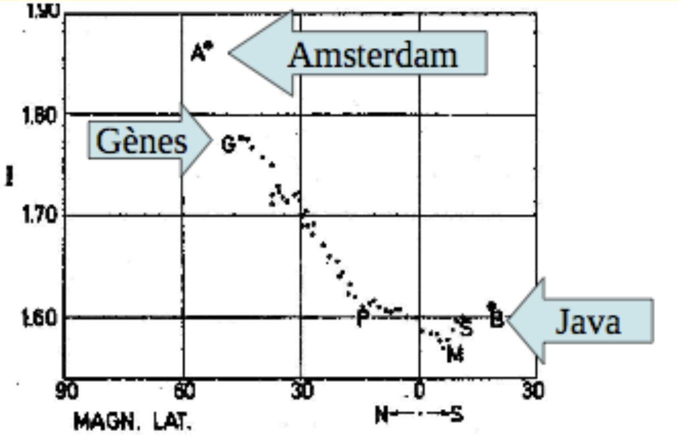
Millikan - Compton controversy

Solved by Jacob Clay on a trip from Genova to Java



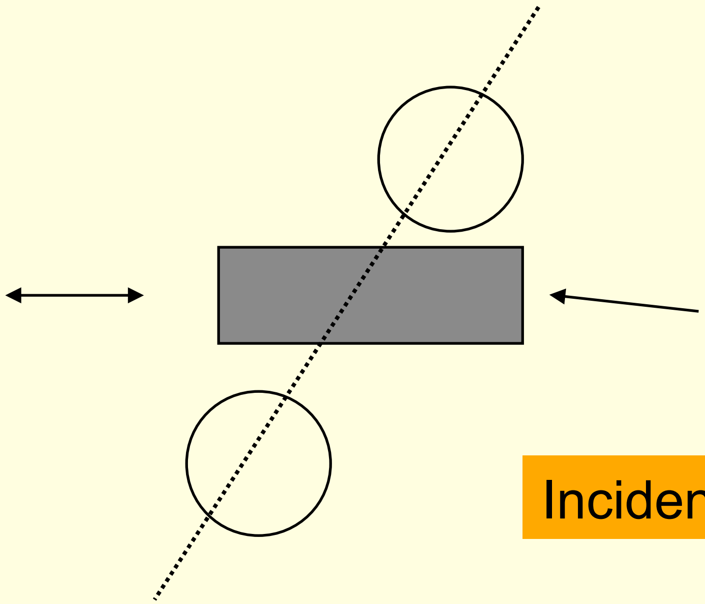


1. Variation of the intensity of the ultra-radiation with the Earth magnetic latitude.

Cosmic rays are charged!

Geiger counter developped in 1912-1928 proved to be very useful for studying cosmic rays

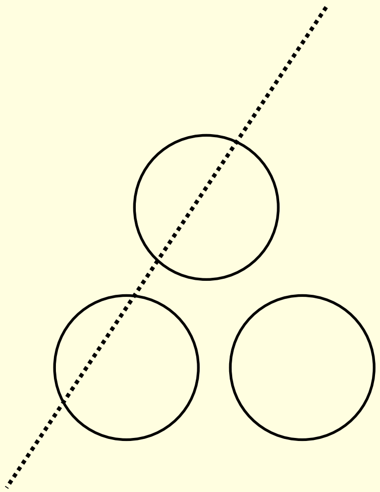
coincidence method



absorber makes no difference

Incident particles come preferentially from the zenith

1933 Rossi



No single particle can hit
the three detectors

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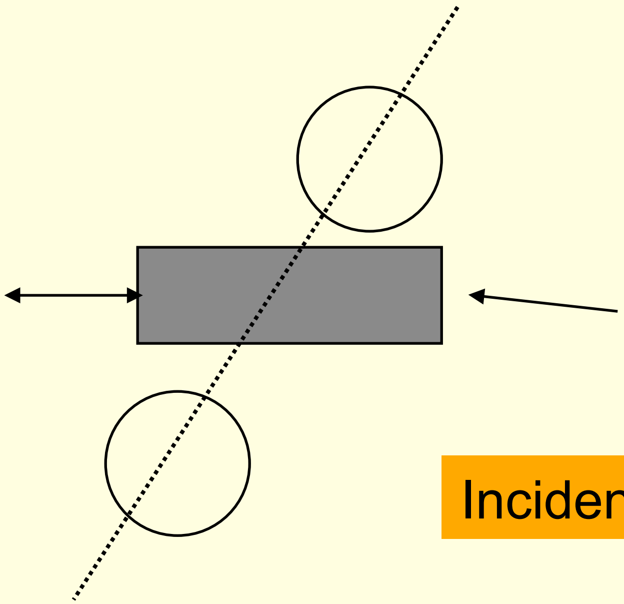

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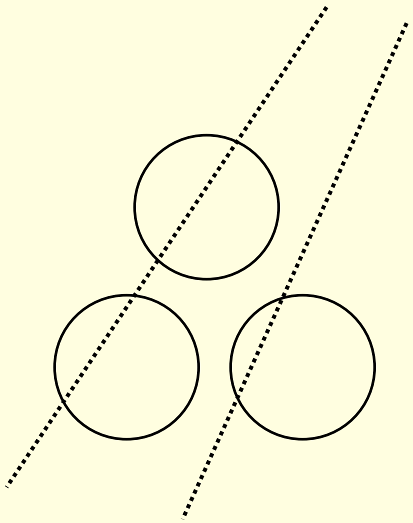


No single particle can hit
the three detectors

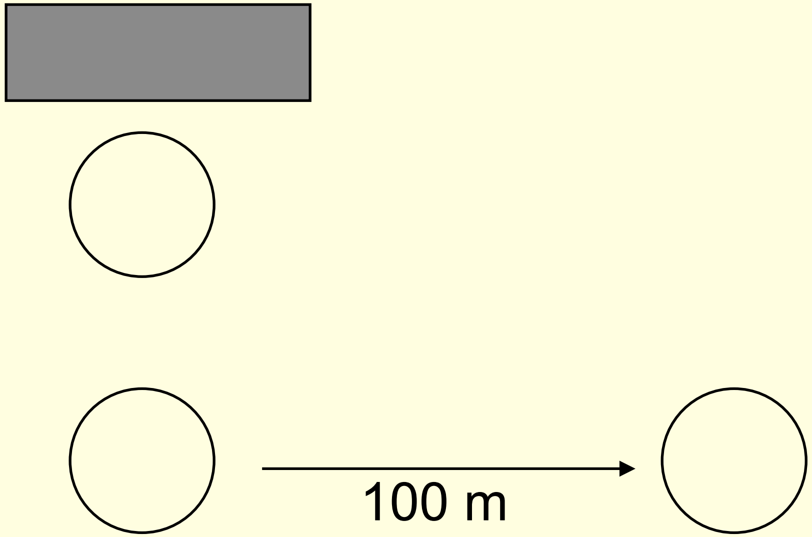
Triple coincidences are observed!

Several particles arrive in coincidence:

cosmic ray showers

In late '30s, Pierre Auger and collaborators study these showers

Jungfraujoch (alt. 3500m)

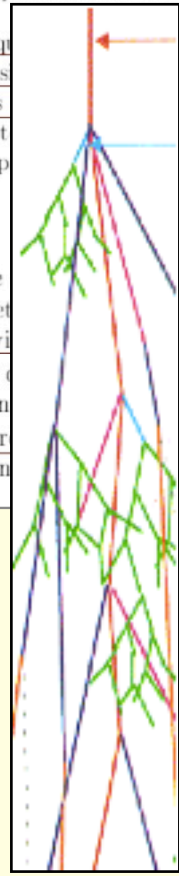


PHYSIQUE NUCLÉAIRE.- *Les grandes gerbes cosmiques de l'atmosphère.* Note[1] de MM. **PIERRE AUGER** et **ROLAND MAZE**, présentée par M. Jean Perrin.

1. Nous avons montré[2] l'existence de gerbes de rayons cosmiq ... ns
l'atmosphère et dont les branches peuvent être distantes de plus ... us
avons pu étendre cette étude jusqu'à des distances de plusieurs ... res
et mettre ainsi en évidence les effets de corpuscules de trés haut ... ur
traversée de l'atmosphère. La mesure du pouvoir pénétrant des p ... es

(...)

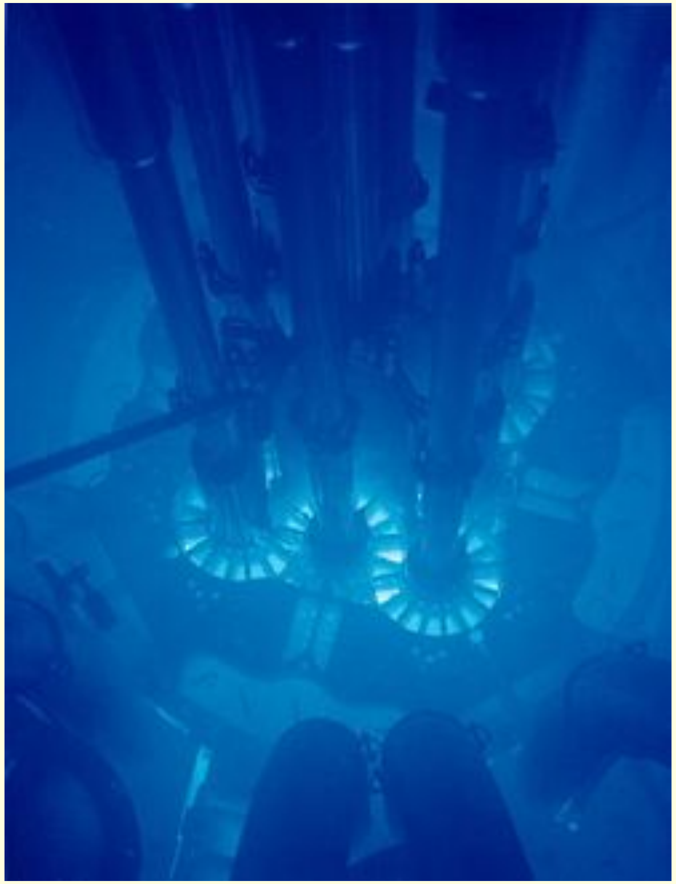
3. On voit d'après ces résultats que les averses soudaines de ... es
décrites ici peuvent couvrir des surfaces de l'ordre de 1000 m^2, et ... c
plusieurs dizaines de milliers de corpuscules, dont une moitié envi ... er
5 cm de plomb. Si l'on évalue à 5×10^7 eV la perte d'énergie ... es
(supposés être des électrons lourds) par centimètre de plomb, on ... ie
totale de la gerbe, et par conséquent du corpuscule initial qui la pr ... le
10^{12} à 10^{13} eV. Les particules d'énergie aussi élevées sont certain ... re



Energy of the primary particle can reach 10^{15} eV (1000 TeV)!

What is the source of such particles?

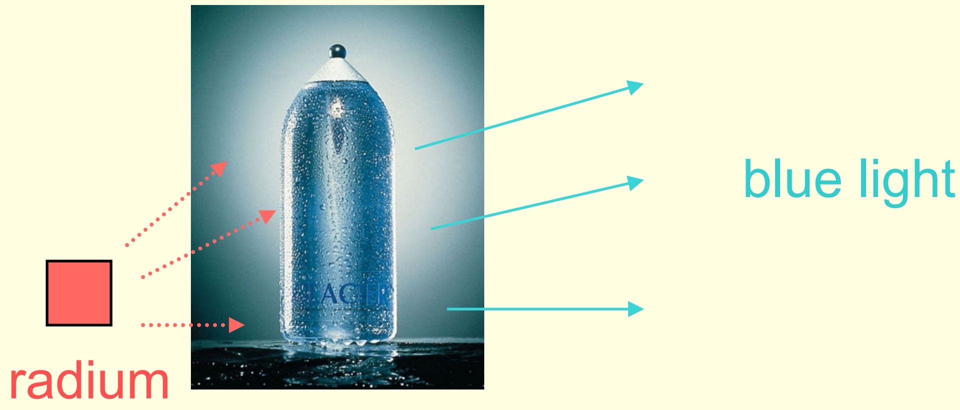
2. The light of particles



nuclear reactor pool

Many astroparticle observatories use Cherenkov radiation to detect high energy particles.

Early ‘30s, young Ph.D. student Pavel Cherenkov is asked to study this blue light



Is this fluorescence?

Fluorescence is associated with the emission of a photon by an excited molecule returning to its fundamental state.

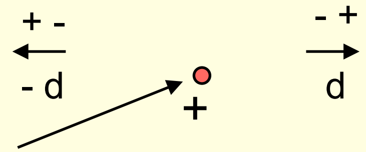
Cherenkov: no, because the phenomenon does not depend on the type of liquid

1937, Frank and Tamm: a (light) shock wave due to the fact that the energetic charged particles travel at a velocity larger than the speed of light.

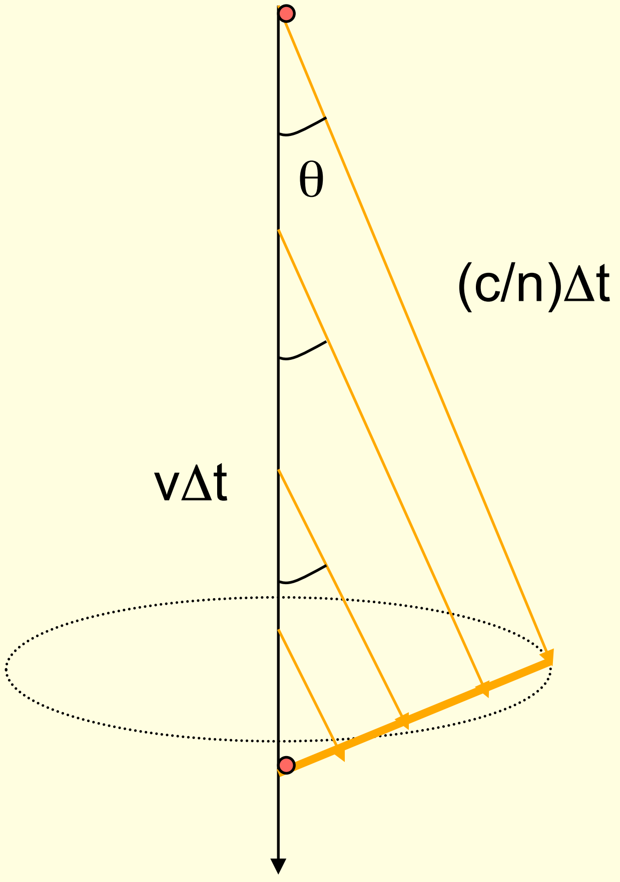
In a medium of index n, light travels at a speed c/n

Hence, particles can travel at velocity v > c/n

Polarization of a medium



positive charge at rest or in slow motion



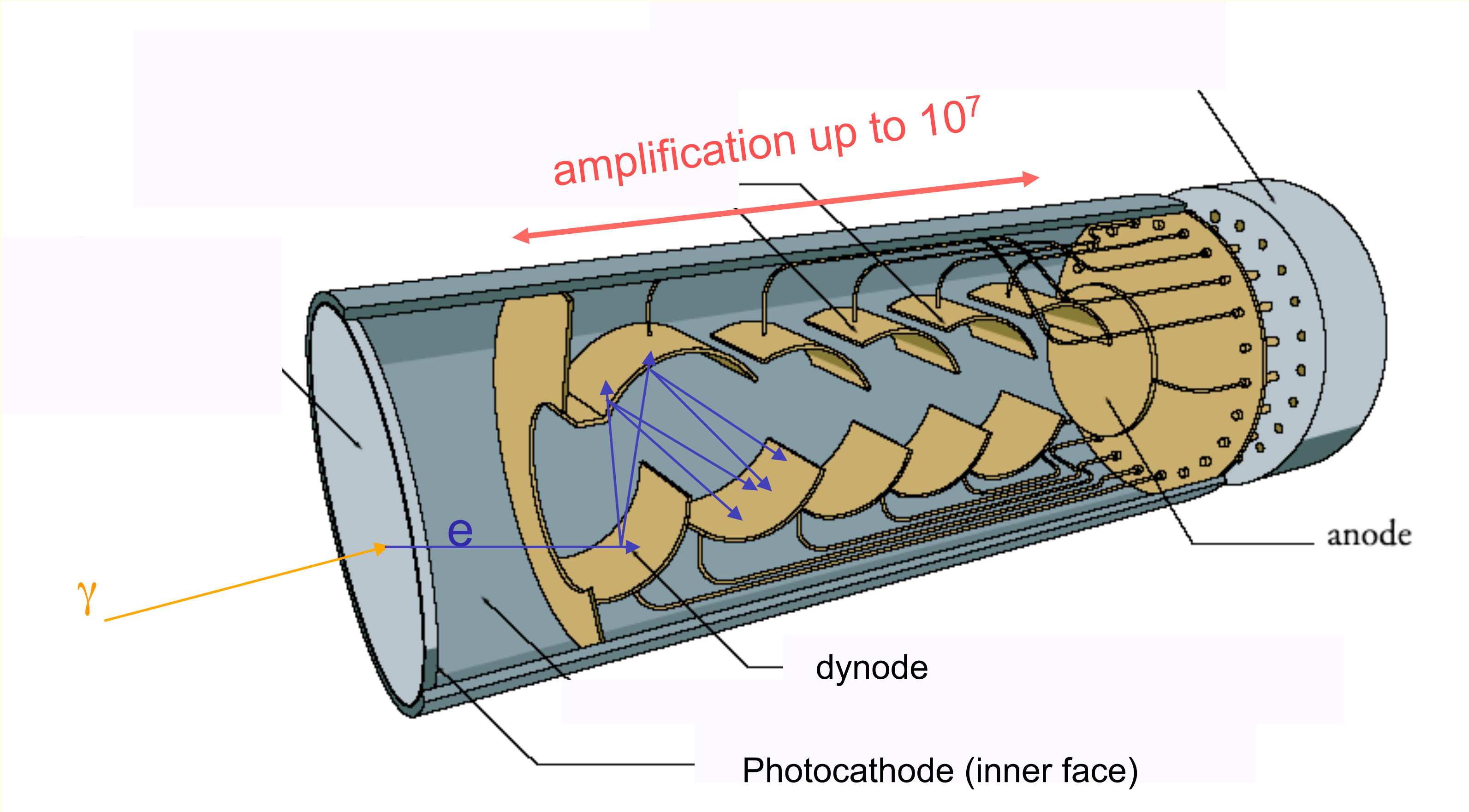
In direction θ, all light waves emitted successively by the particle interfere constructively :

$$\cos\theta = \frac{(c/n)}{v}$$

θ= 1° in air

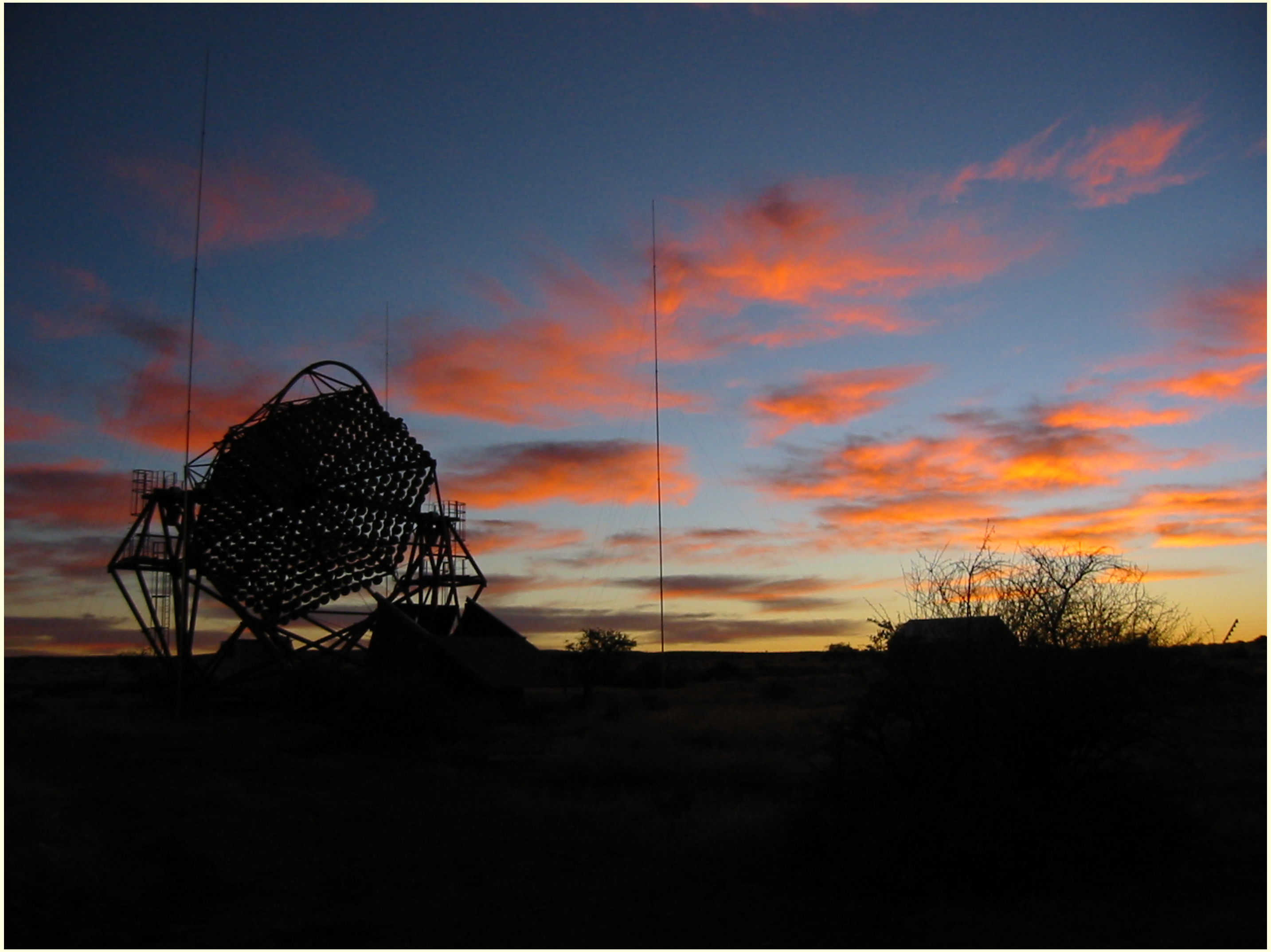
42° in water

How to collect this light? Photomultipliers

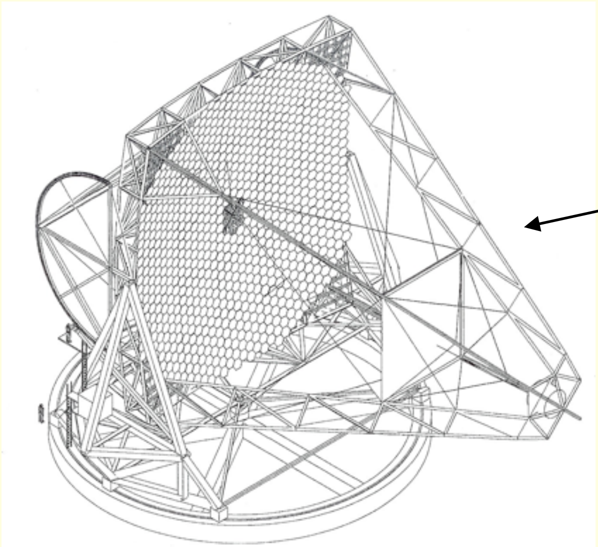


Examples of photomultipliers

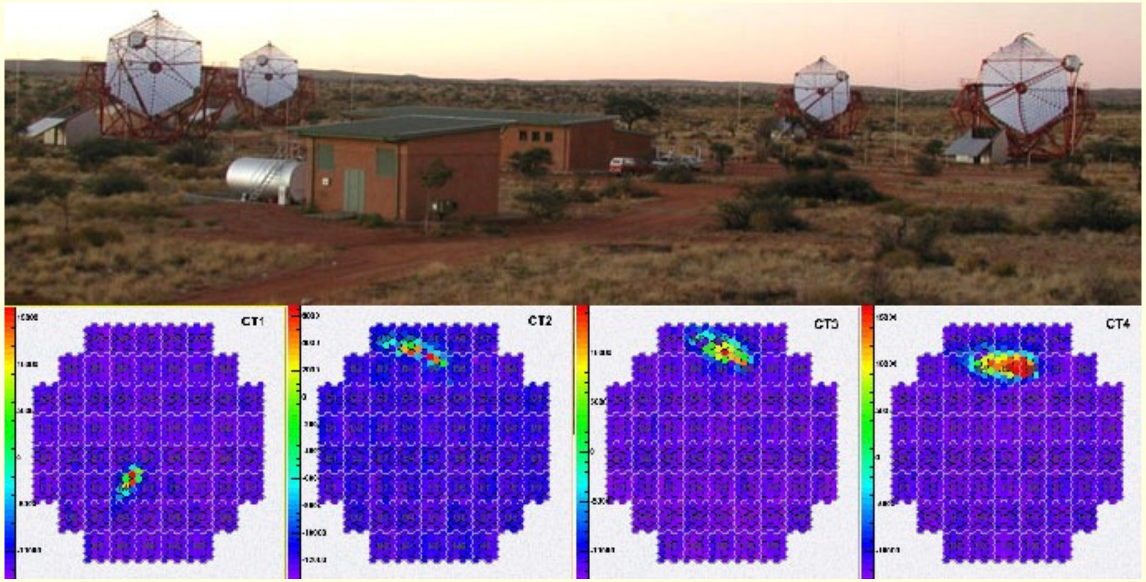
Detecting high energy gammas through their Cherenkov light:
the Cherenkov telescopes of the HESS experiment in Namibia



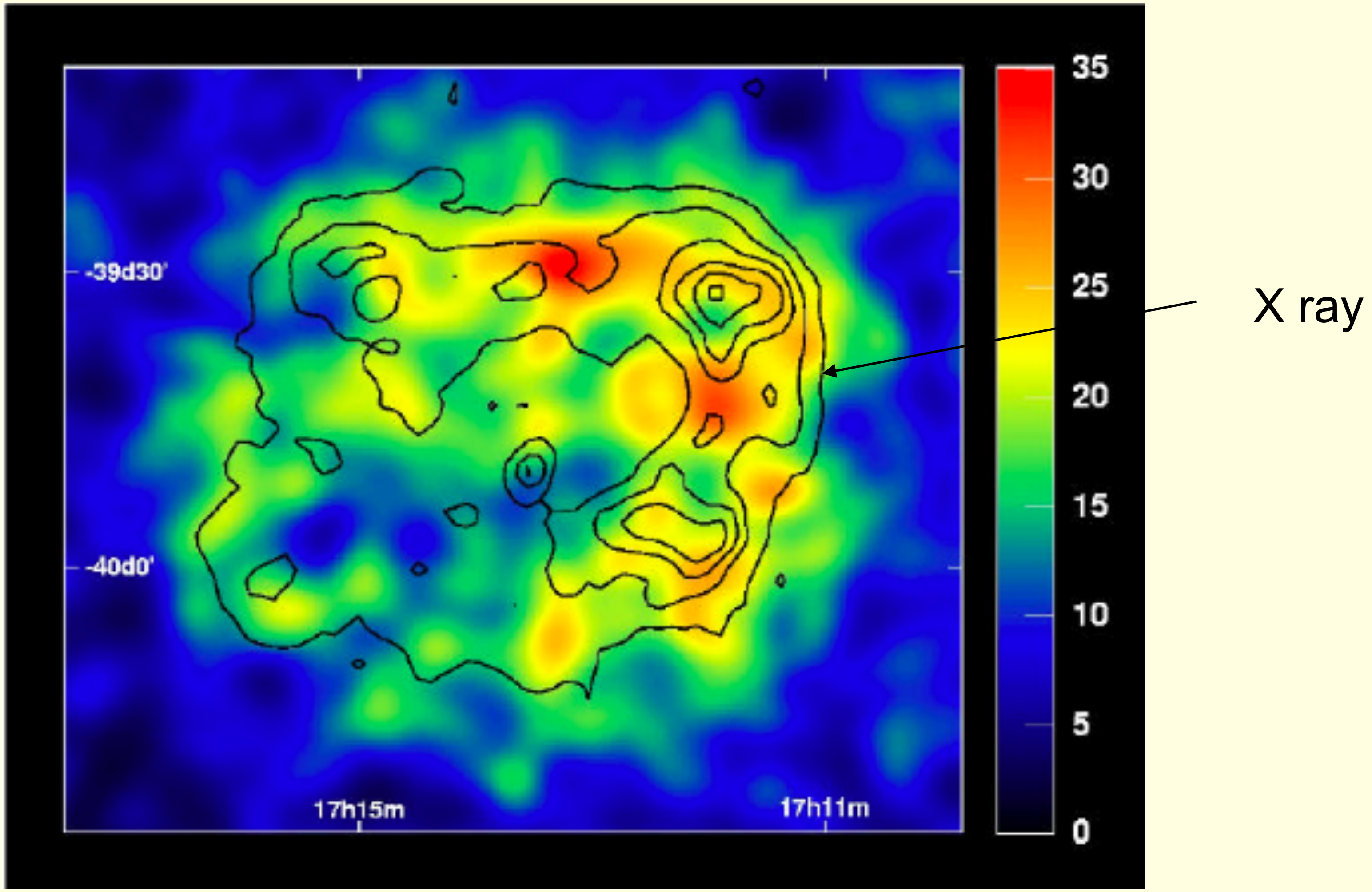
Detection of gamma rays in the 100 GeV to 10 TeV range



one HESS telescope



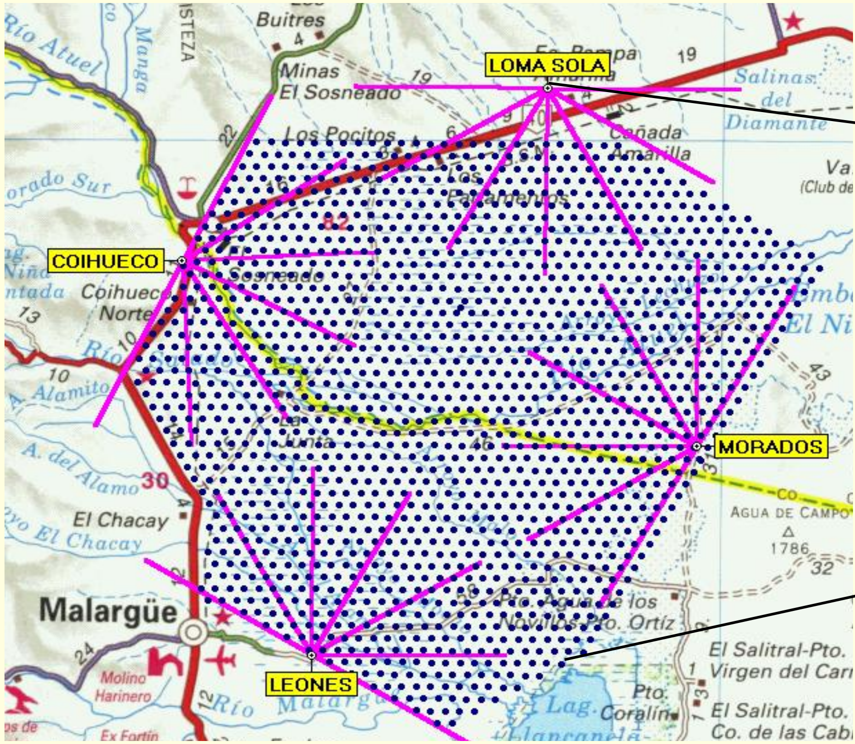
stereoscopic view



Detection of the shell structure of a supernova remnant

<u>The Pierre Auger observatory</u>

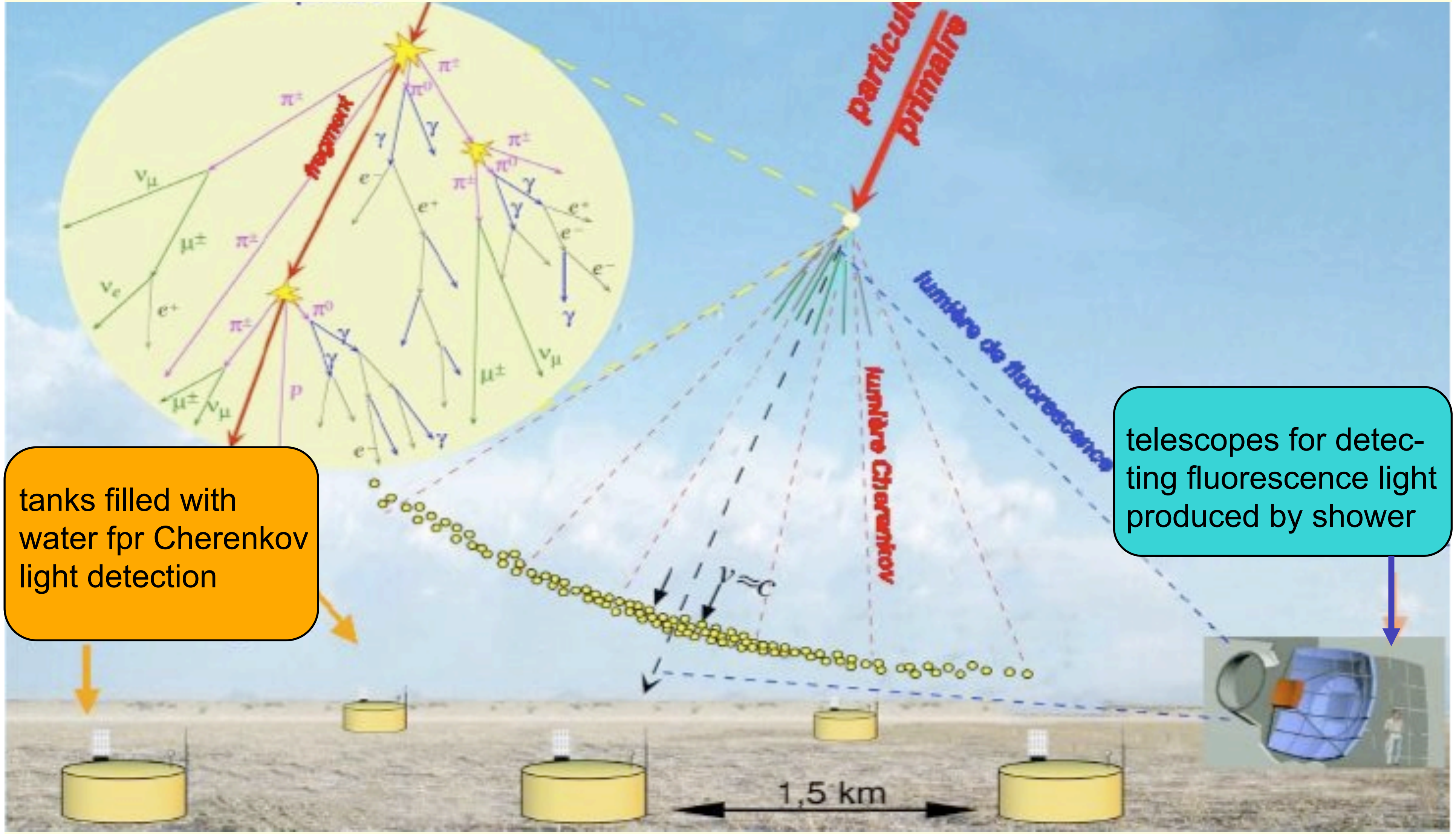
To study the cosmic ray showers of the highest energy, one needs to instrument a very large area



fluorescence detectors

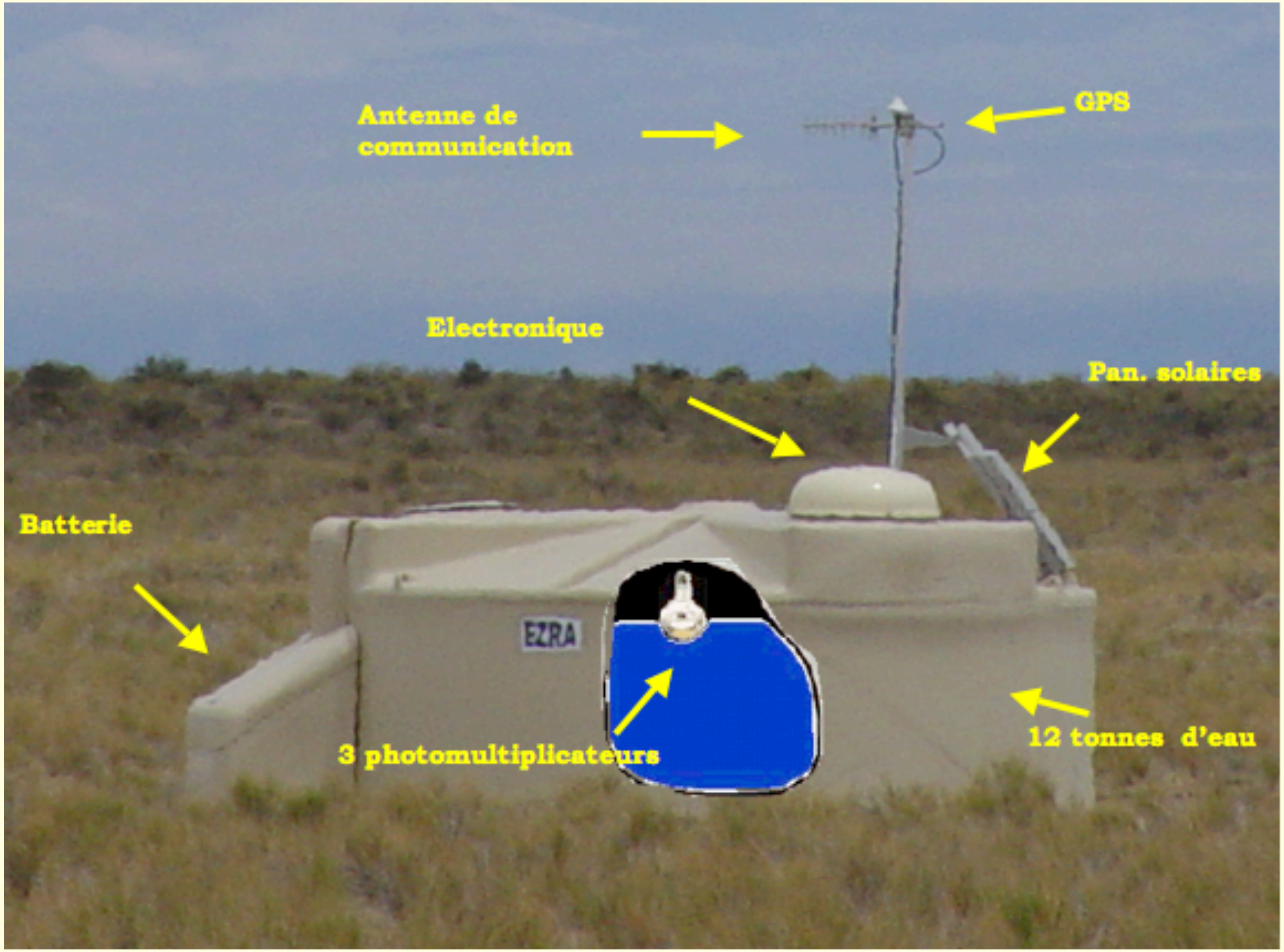
Cherenkov detectors

In Argentina, the Pierre Auger Observatory uses an array of 1600 detectors to cover an area of 3000 km^2

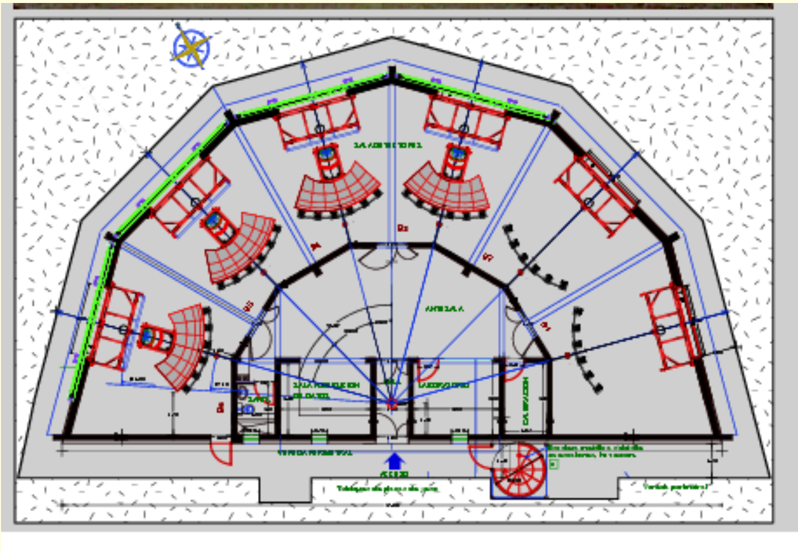


particule primaire
fragment
lumière de fluorescence
lumière Cherenkov
v≈c
1,5 km
tanks filled with water fpr Cherenkov light detection
telescopes for detecting fluorescence light produced by shower

One tank of Auger (Cherenkov light)

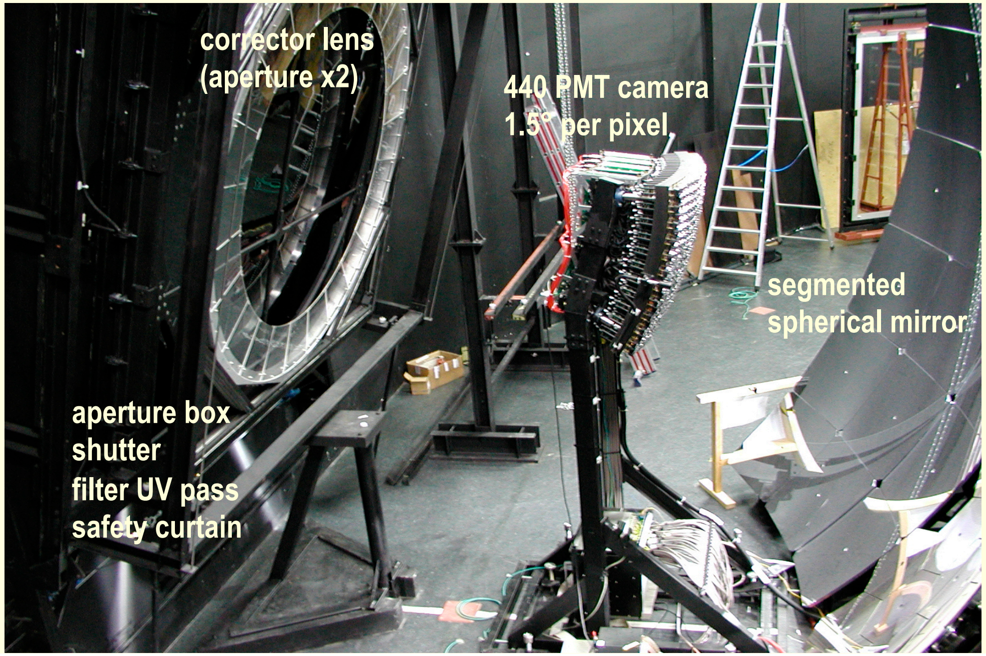


Fluorescence detectors

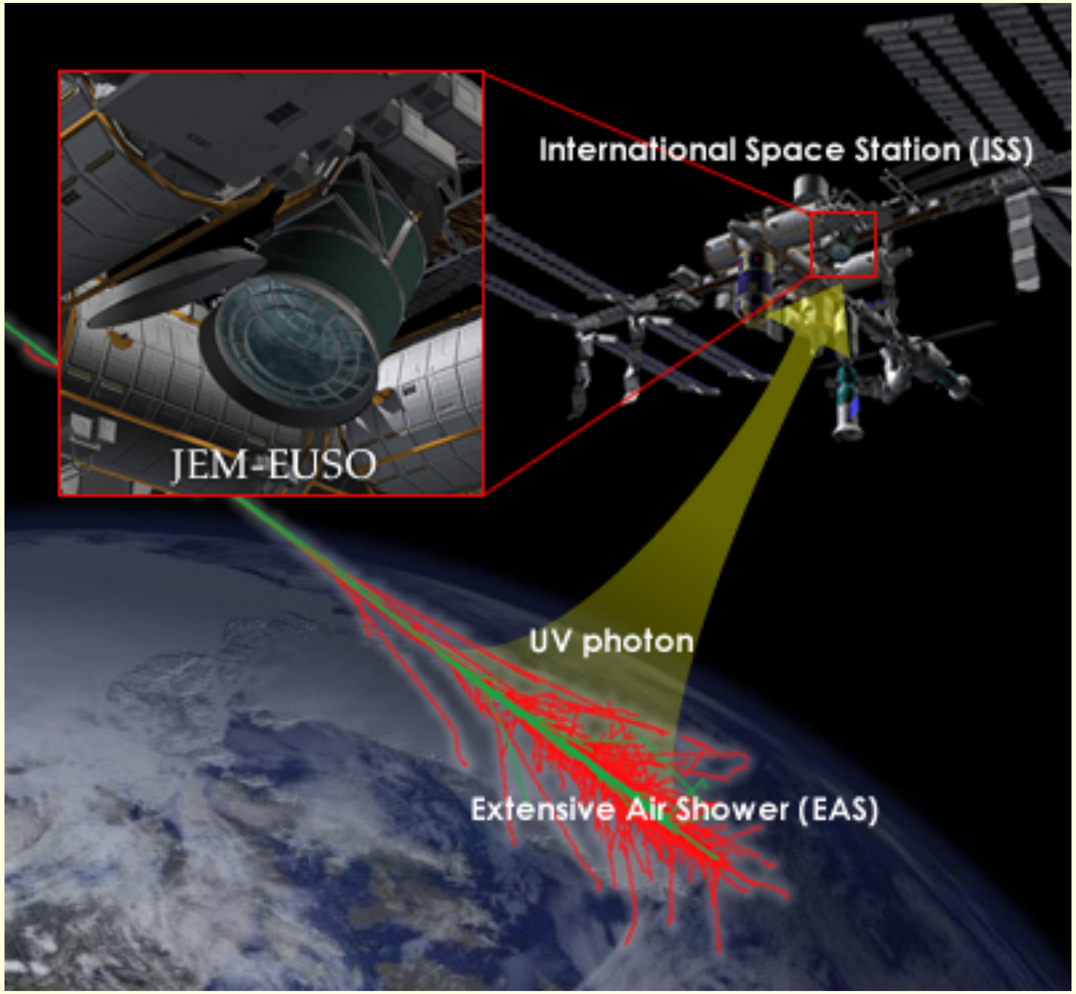


Internal lay out

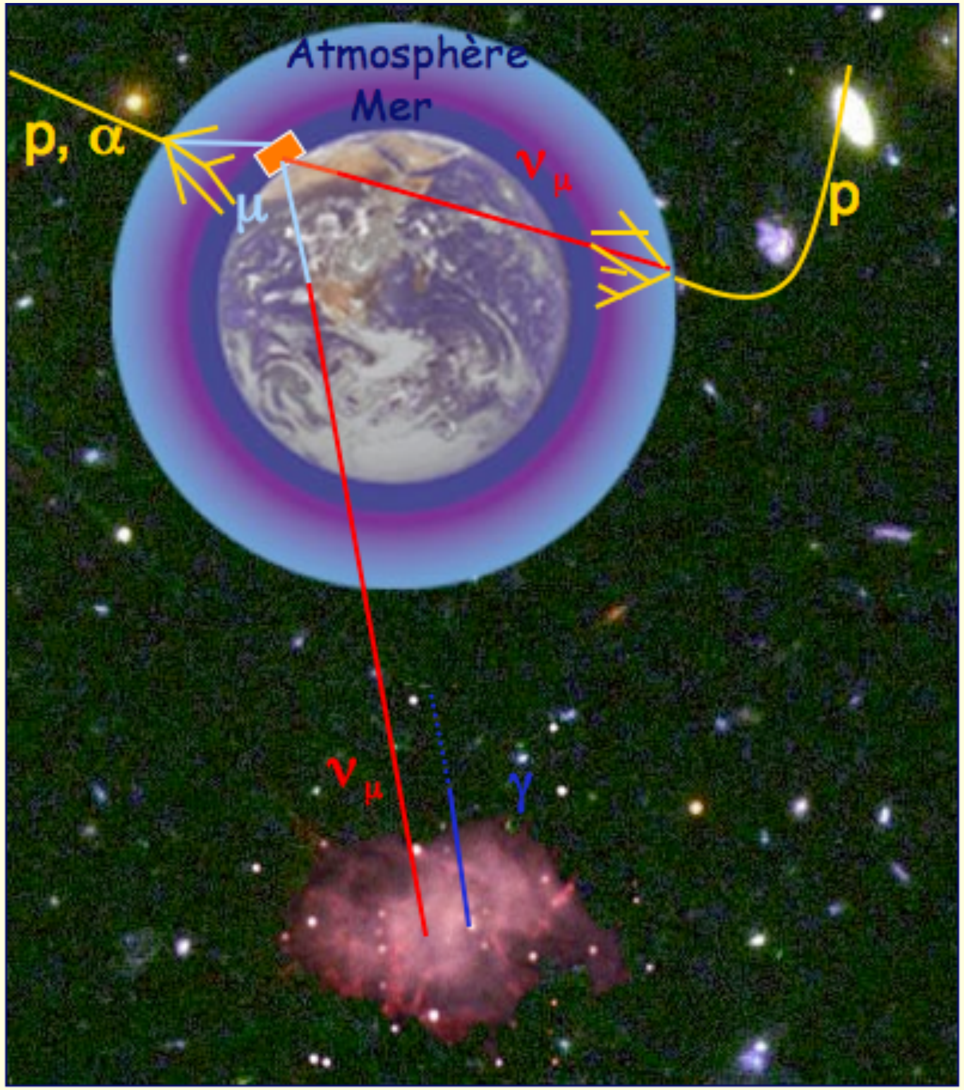
optical system



Using fluorescence to observe these showers from space: JEM-EUSO on the ISS



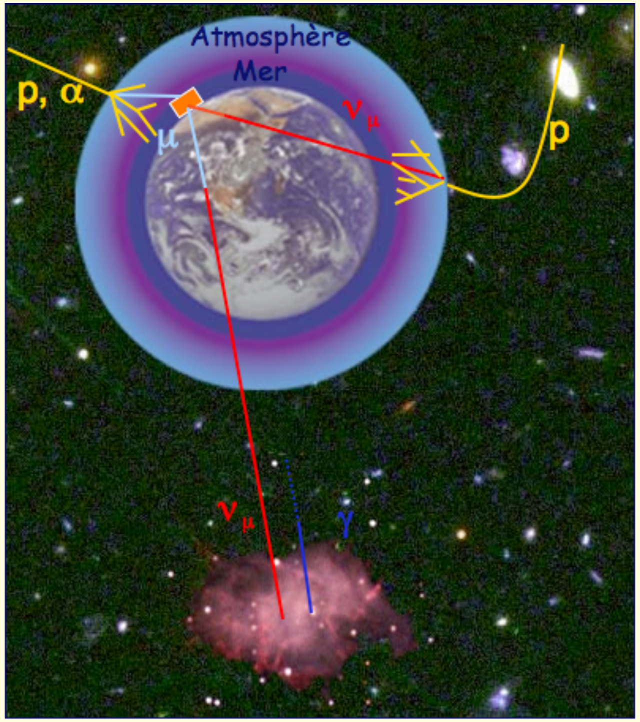
3. Detector Earth



Neutrinos are very difficult to detect because of their small cross section

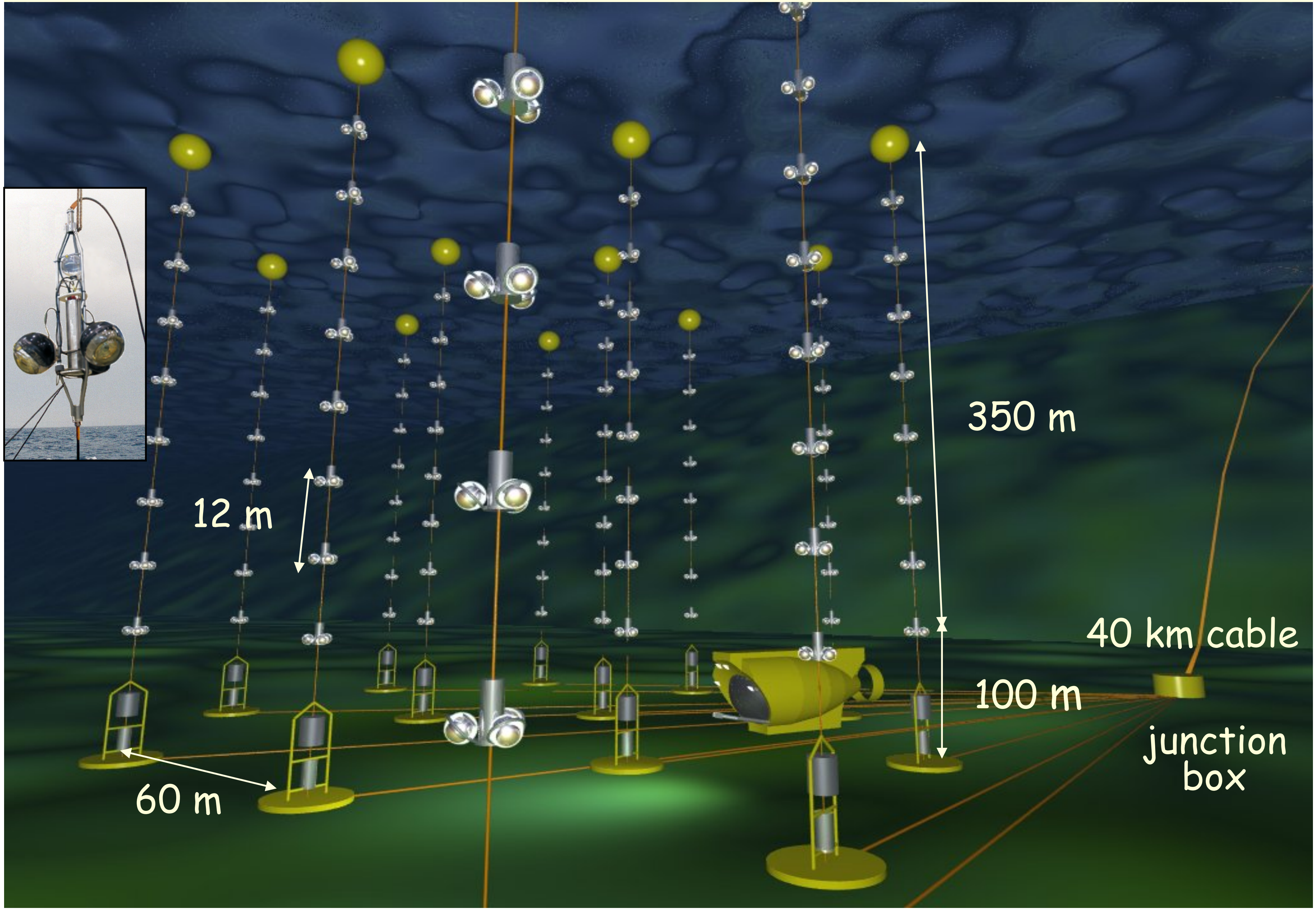
e.g. neutrinos produced in the Sun reach the Earth with a flux of 60 billion/cm^2, only 1 in 10^{12} are stopped

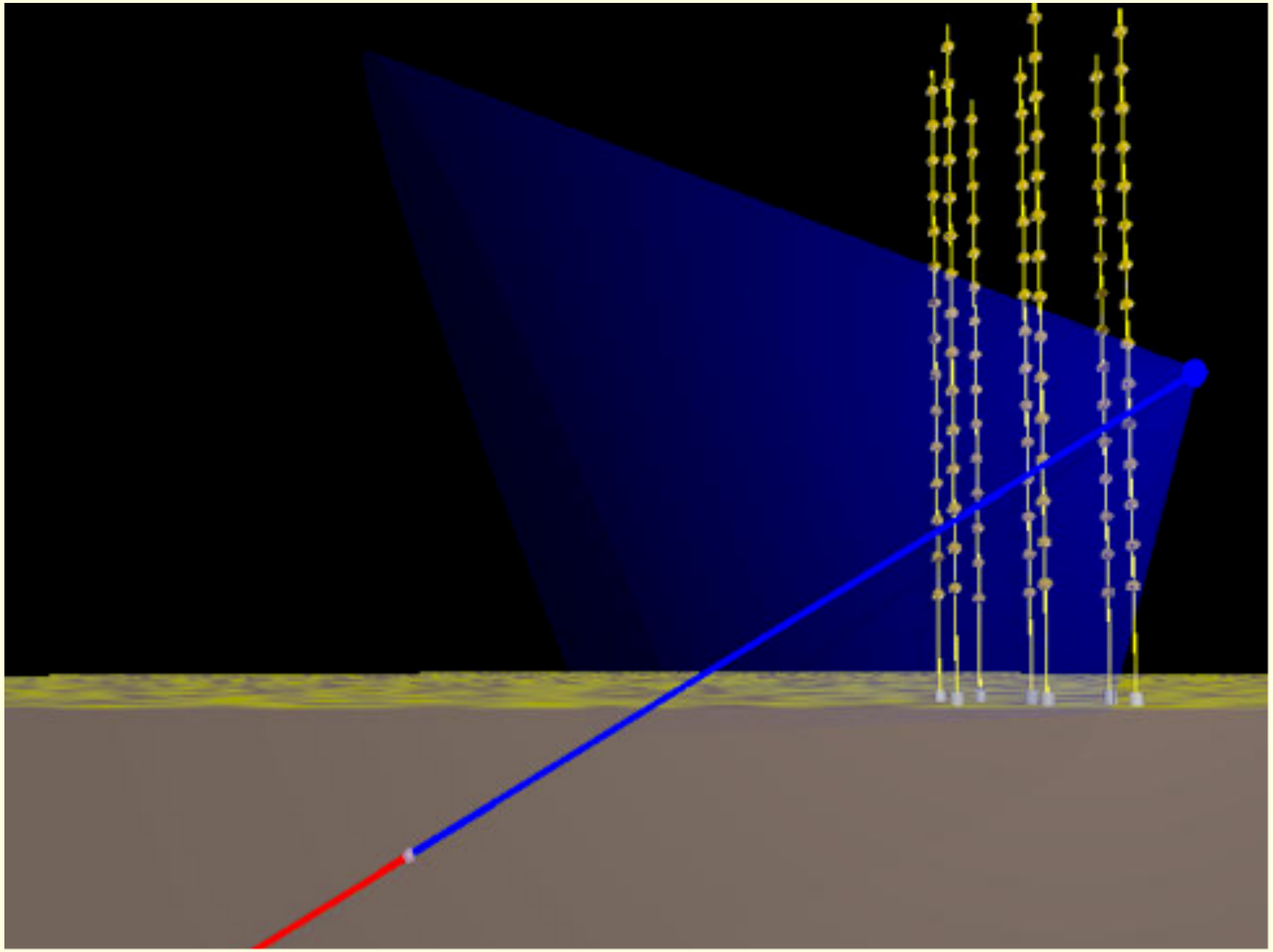
Positive side: cosmic neutrinos arrive on Earth unperturbed
they trace the sources



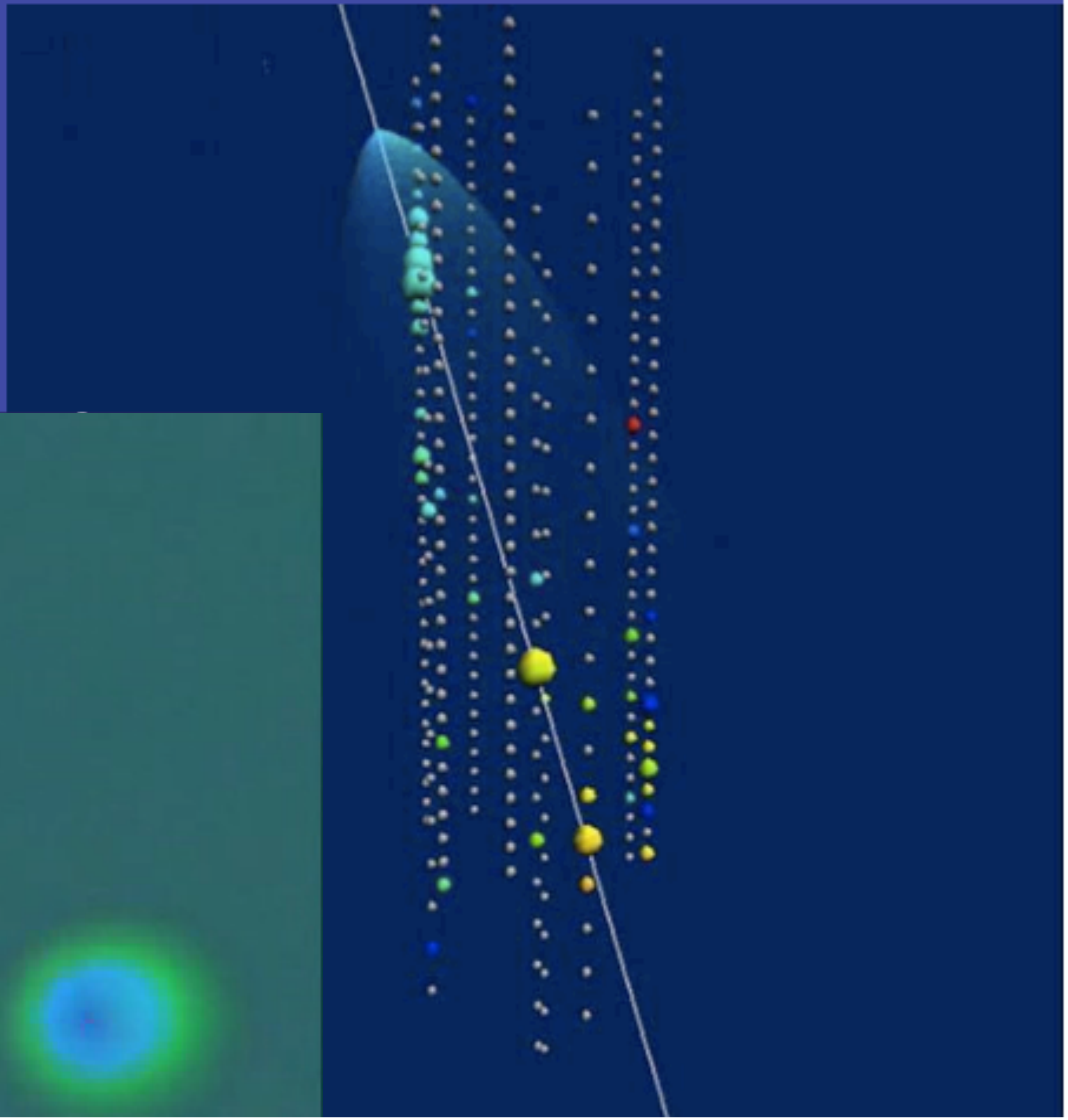
To track the elusive neutrinos, one uses the Earth as detector.

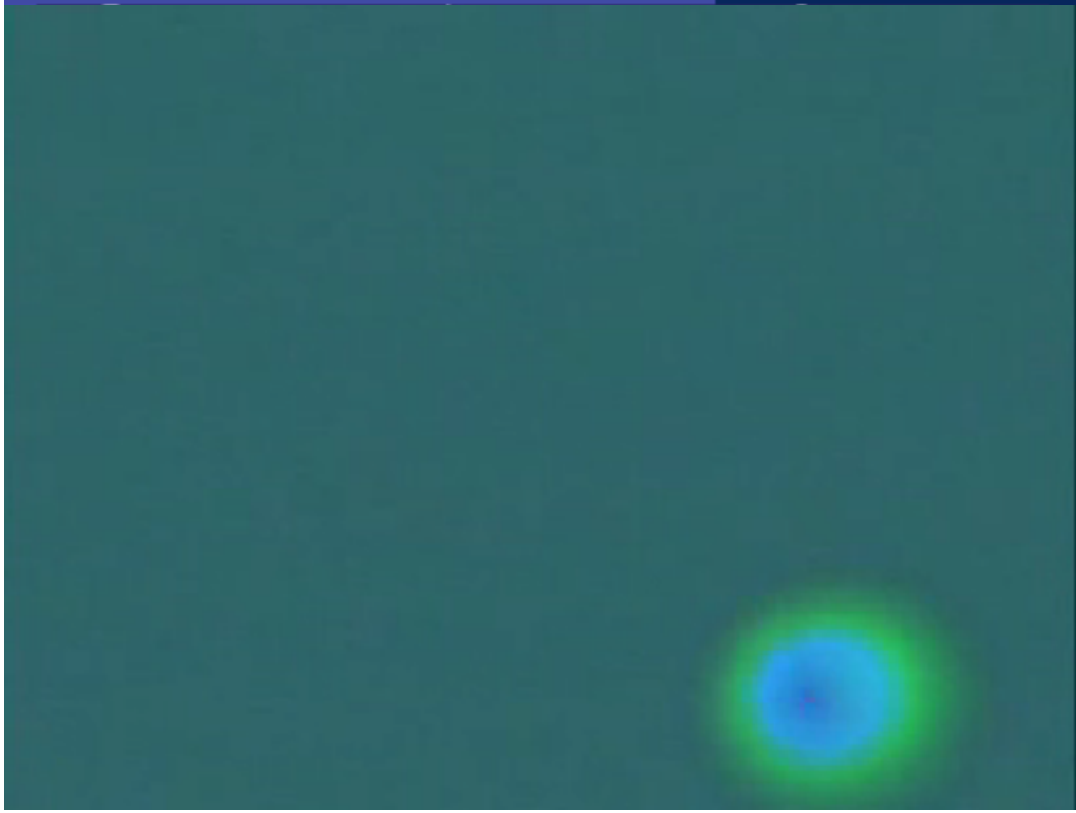
Example of ANTARES in the Mediterranean



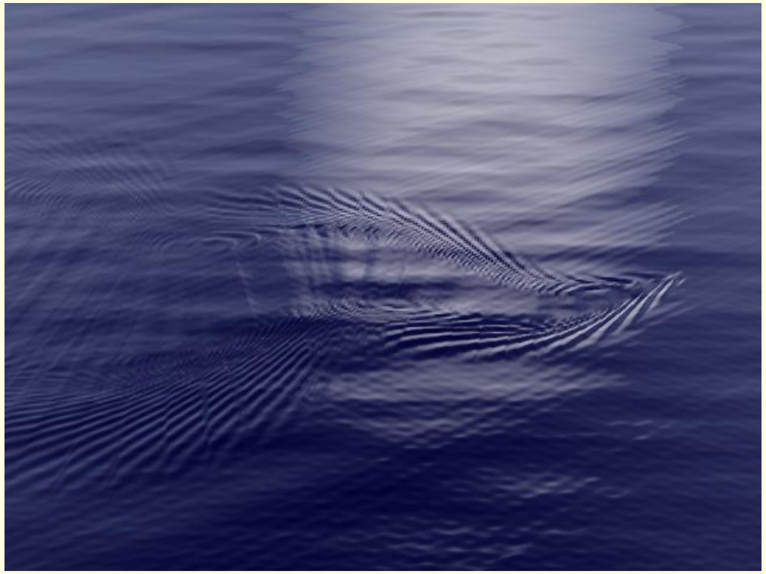


IceCube: the under-ice detector at the South Pole

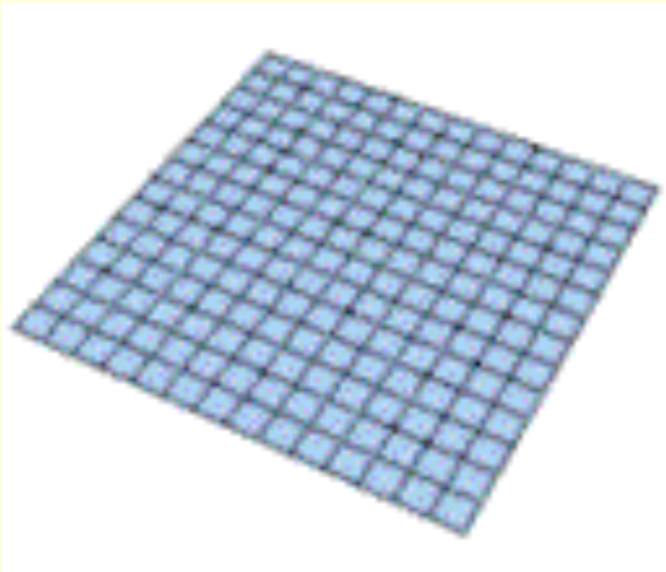




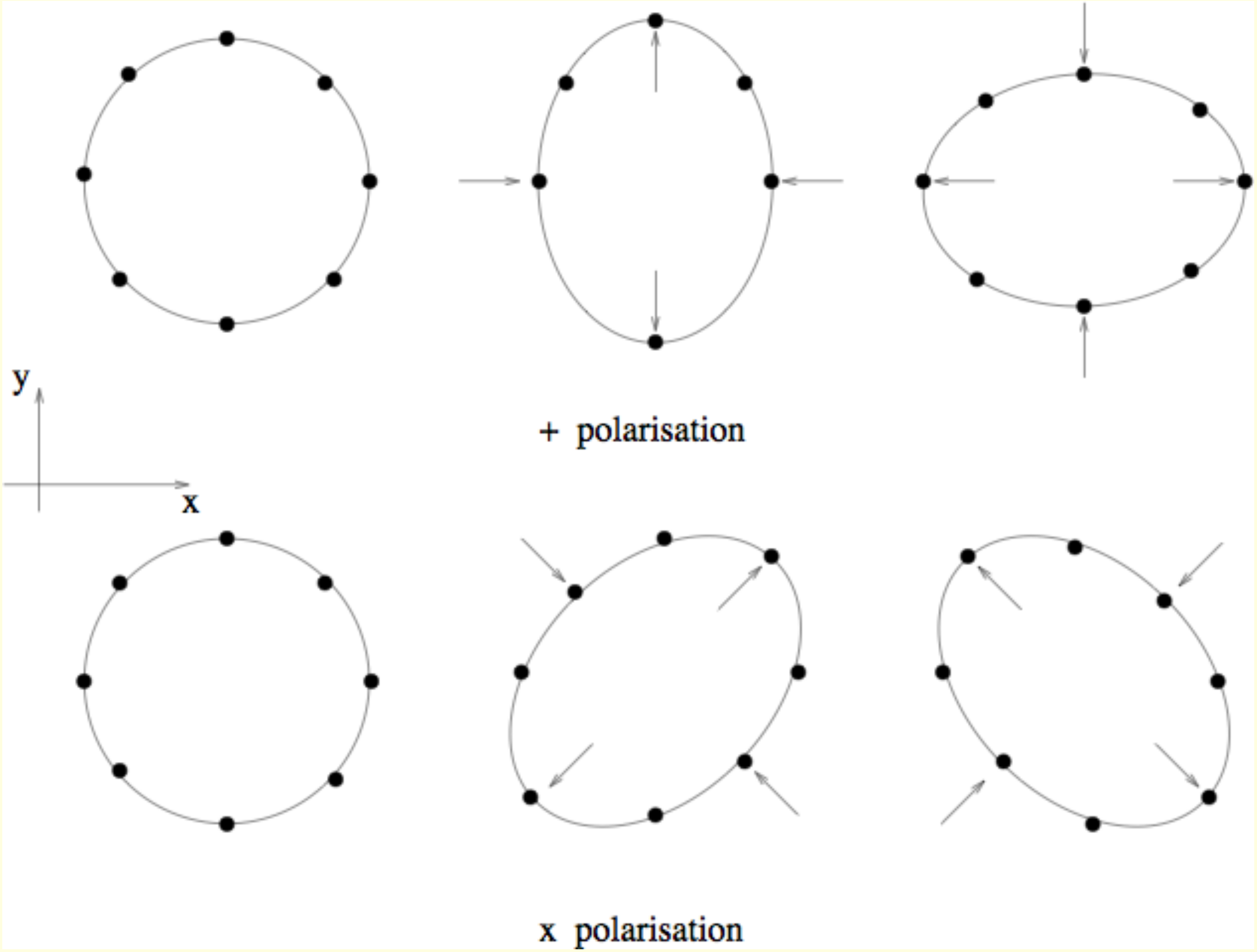
4. Ripples of space-time



Space-time (4D) is « elastic ».
Any mass or localized form of energy perturbs it and curves it.
Just as when you drop a stone in a pond …



… violent phenomena (sudden motion of bulk of matter) may lead to waves of deformation of spacetime that will propagate in the Universe.



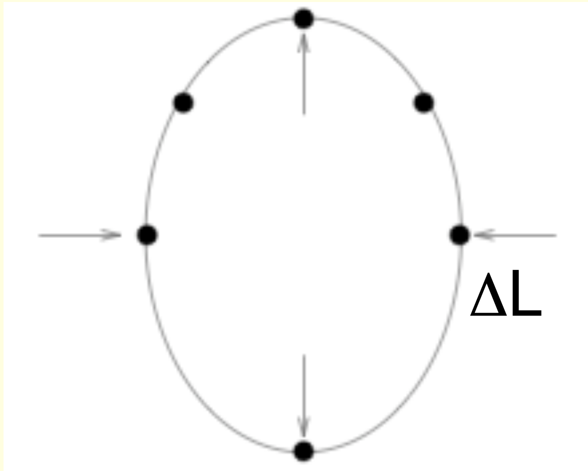
Two types of polarisation for gravitational waves

One introduces the amplitude of the gravitational wave:

$$h = \frac{\Delta L}{L}$$

variation of length due to the gravitational wave (ΔL)

total length (L)



Examples:

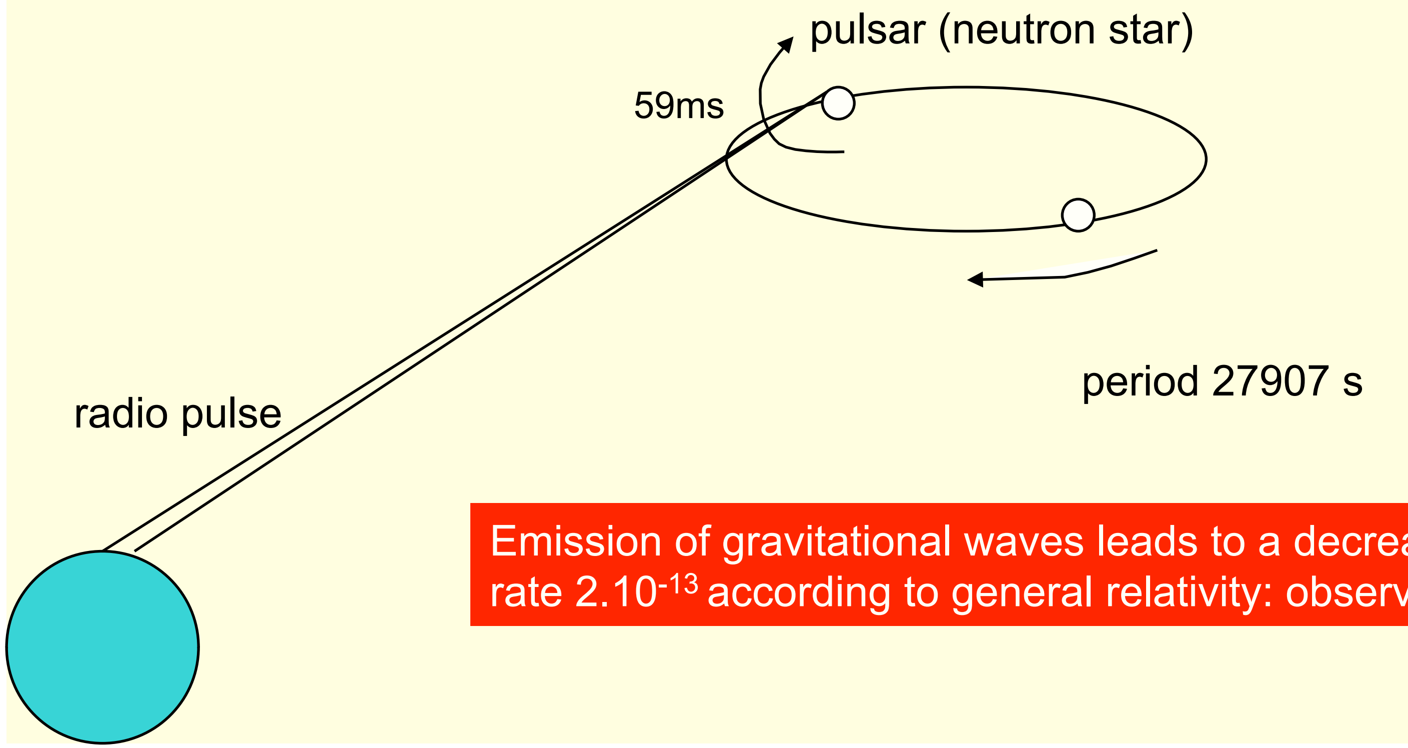
- explosion of a supernova in the Virgo cluster (15Mpc): $h=10^{-21}$ à 10^{-24}

- binary system of 2 black holes ($M=1,4M_{\odot}$) at 10 Mpc: $h=10^{-22}$ à 10^{-23}

1 pc = 3.26 light years = $3\ 10^{16}$ m

Gravitational waves have been detected indirectly!

Binary pulsar PSR 1913 16 (Hulse-Taylor)



Emission of gravitational waves leads to a decrease in the period at a rate 2.10^{-13} according to general relativity: observed by Hulse and Taylor

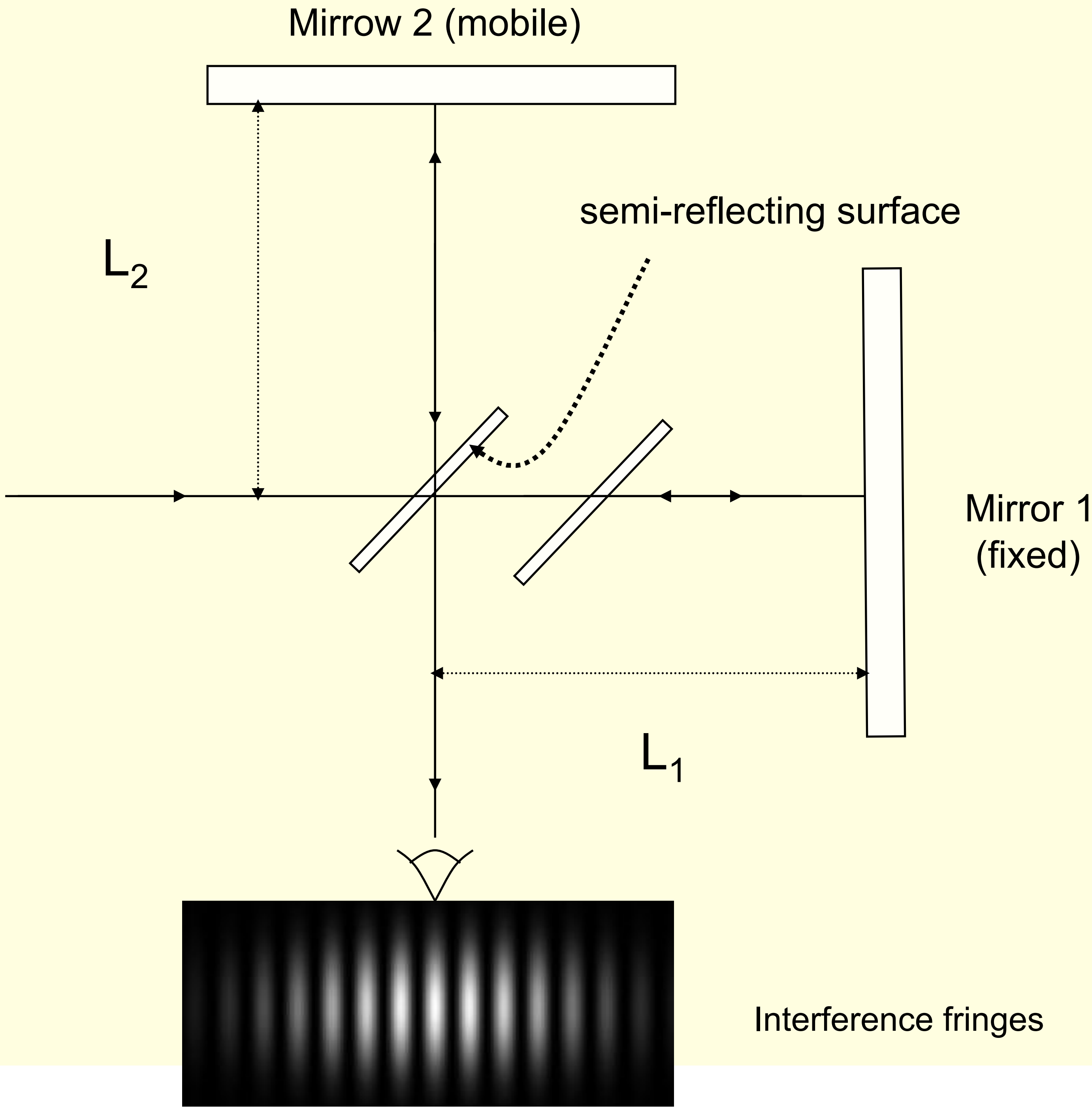
How to detect gravitational waves directly?

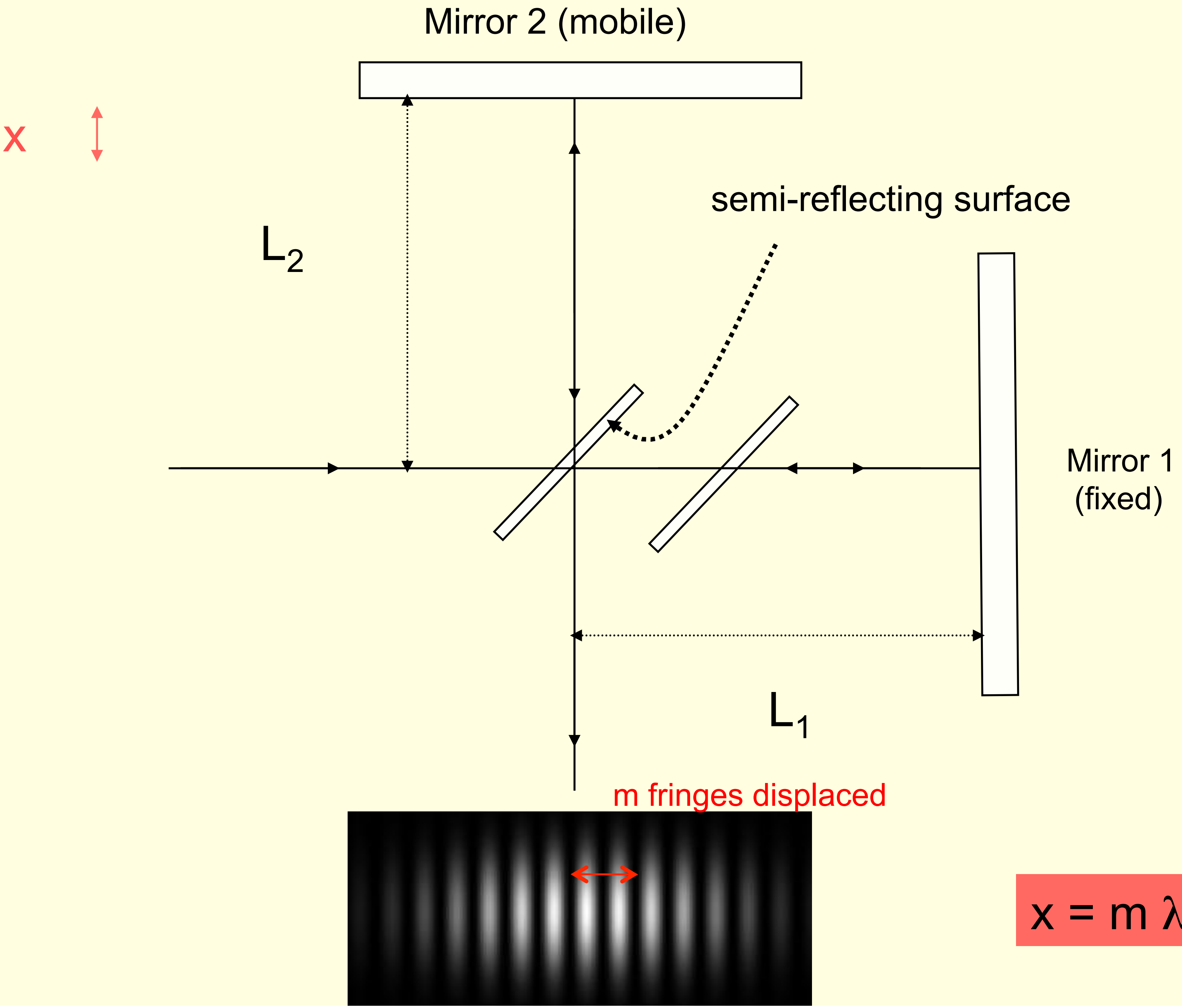
For masses localized at a distance of one kilometer

$$\Delta L = h\,L \sim 10^{-22}\,.\,10^{3} = 10^{-19}\text{ m !}$$

Only known solution : interferometry

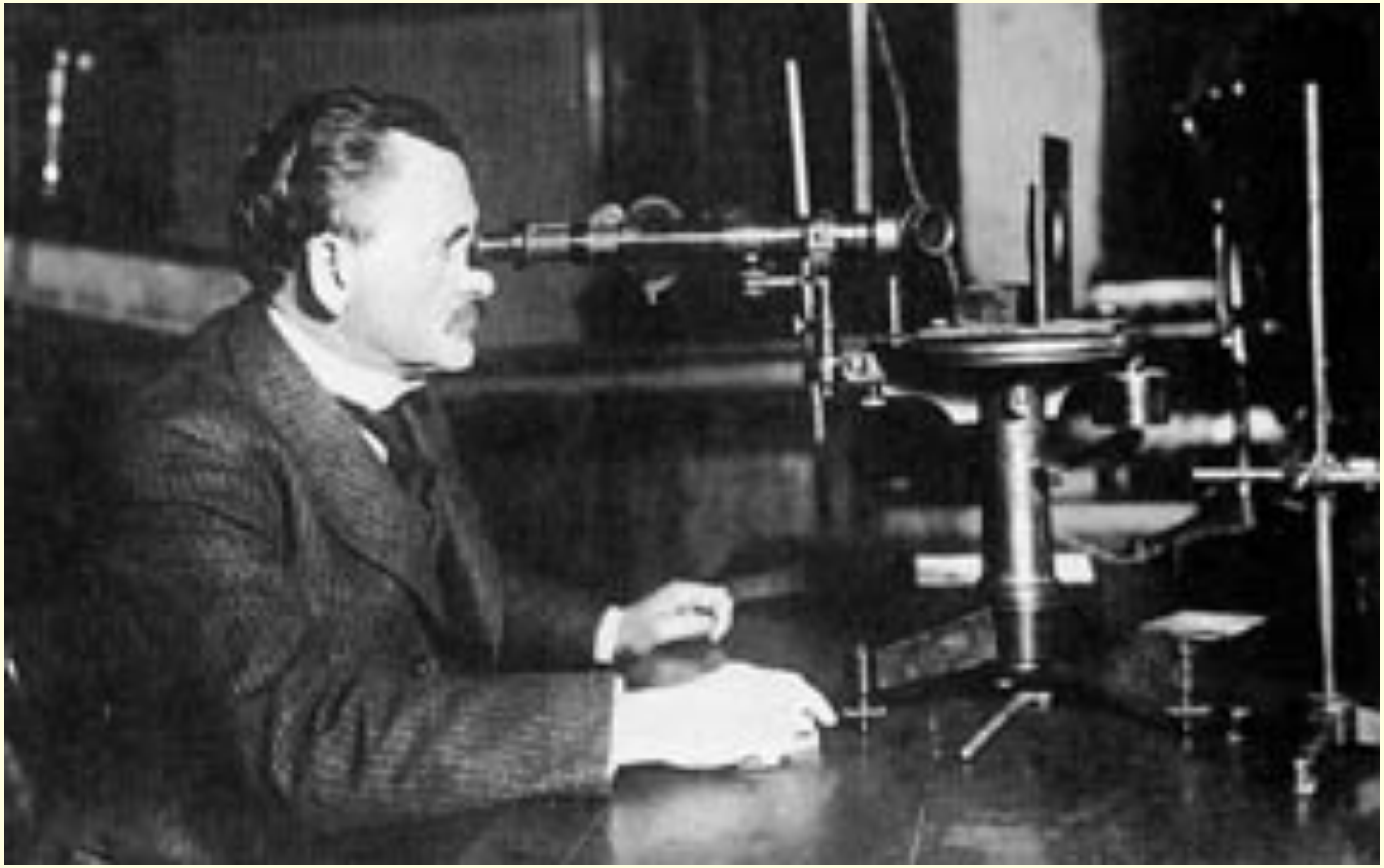
Michelson interferometer




Mirror 2 (mobile)
x
semi-reflecting surface
L2
Mirror 1
(fixed)
L1
m fringes displaced

$$x = m \lambda / 2$$

Albert Michelson counting interference fringes



Sensitivity in 1887: $\Delta L = 6.10^{-10}$ m!

Which size for an interferometer detecting gravitational waves?

Size ~ Wavelength of the gravitational wave

~ c / f

Frequency f of gravitational waves $\sim\sqrt{M/R^3}$

(Kepler law for binary systems)

Neutron stars ($M \sim 1{,}4 M_\odot$) : $f \sim 100$ Hz

$\Rightarrow$ size ~ 3000 km

Ground Interferometers?

Supermassive black holes ($M \sim 10^6\ M_\odot$) : $f \sim 10^{-4}$ à 10^{-2} Hz

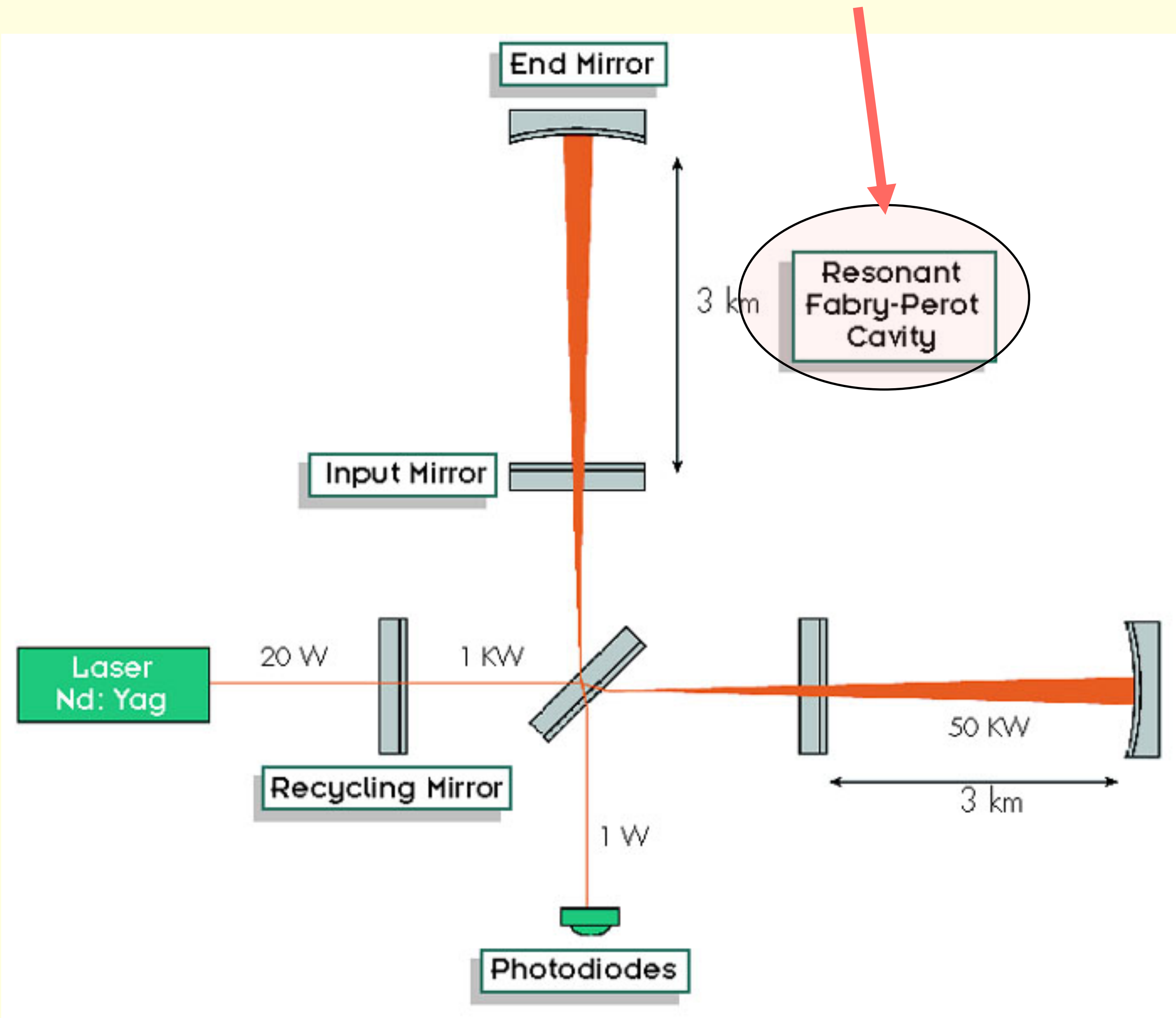
$\Rightarrow$ size ~ 30 million km

LISA

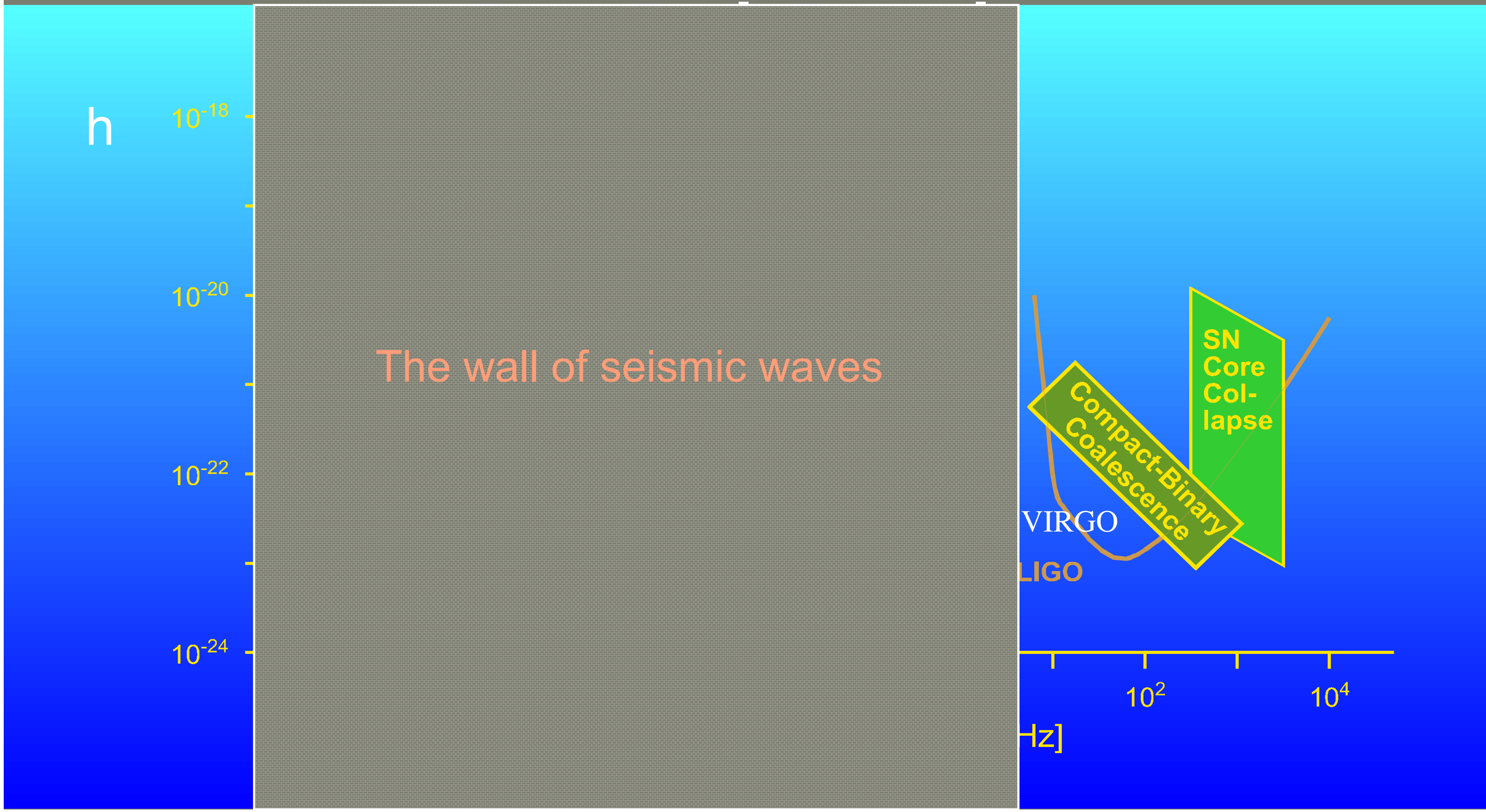
Virgo interferometer near Pisa

Size = 3 km

How to obtain the 3000 km necessary?



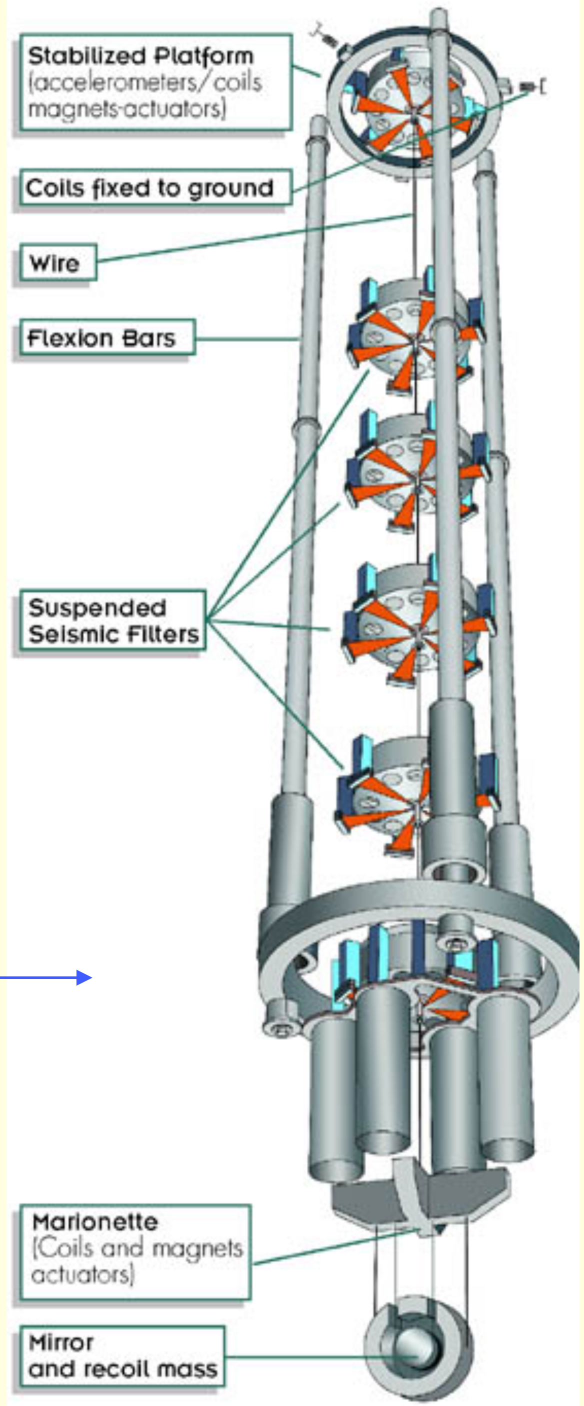
Sensitivity of ground detectors



How to escape as much as possible seismic waves?

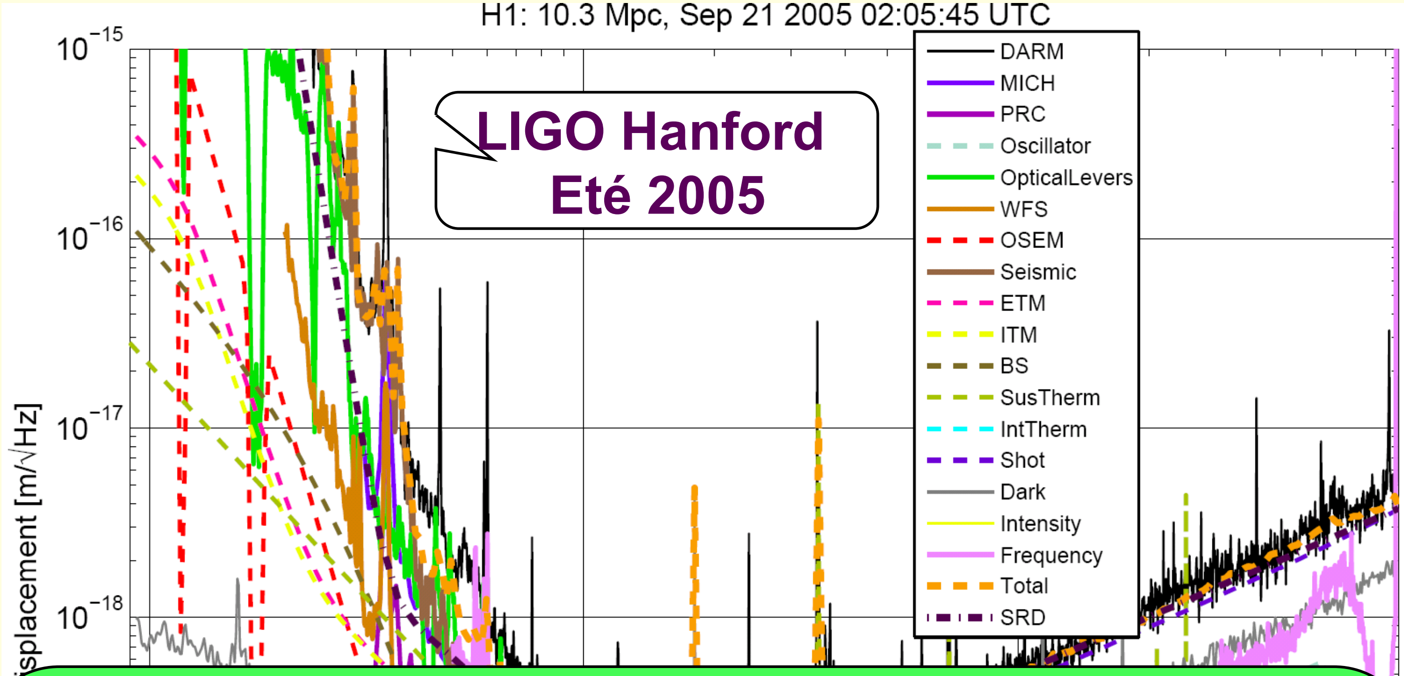
Suspend the interferometer

Virgo suspensions



(ou put it underground)

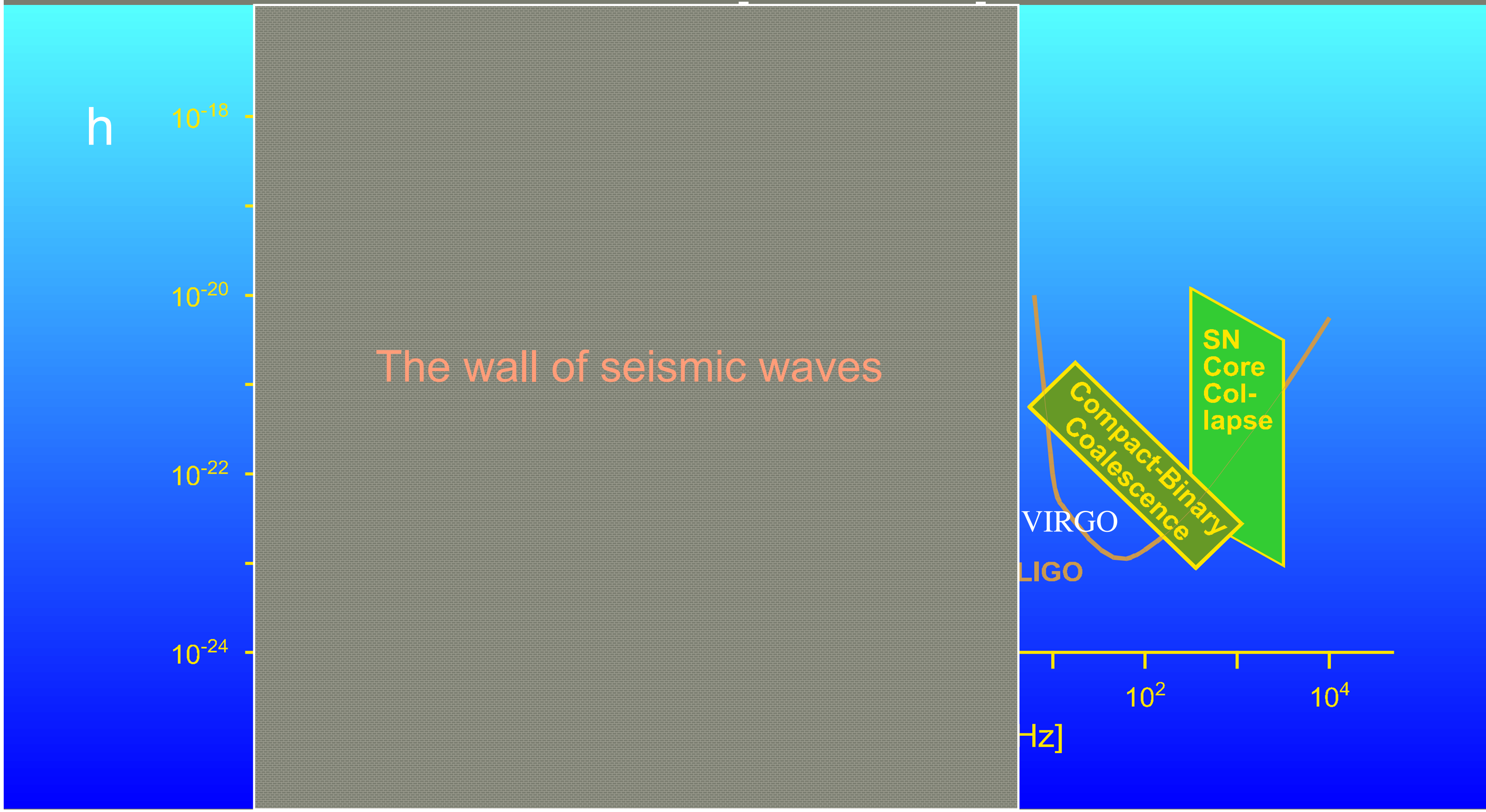
Sensitivity to displacement of ground interférometers



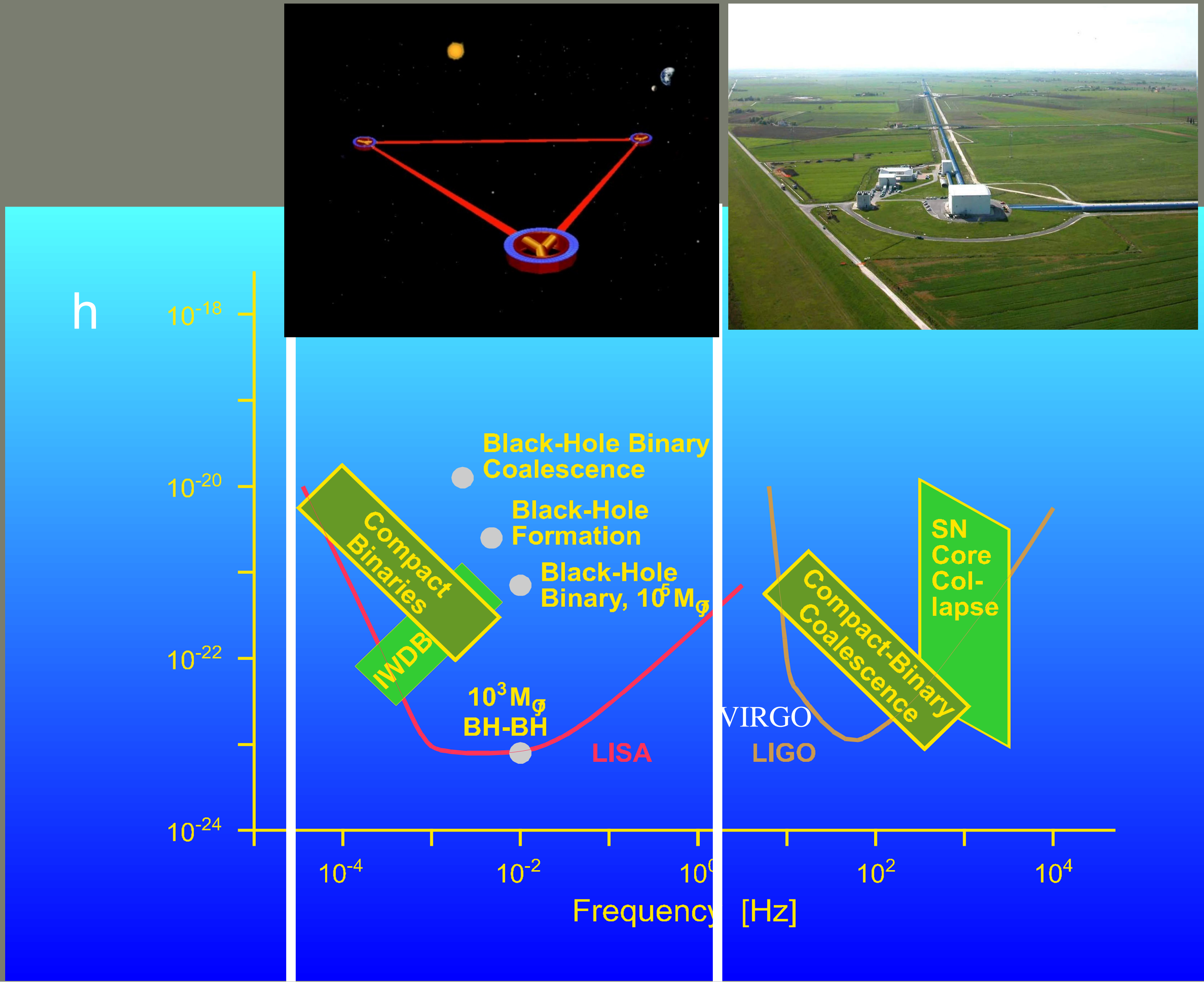
1×10^{-19} m/√Hz!

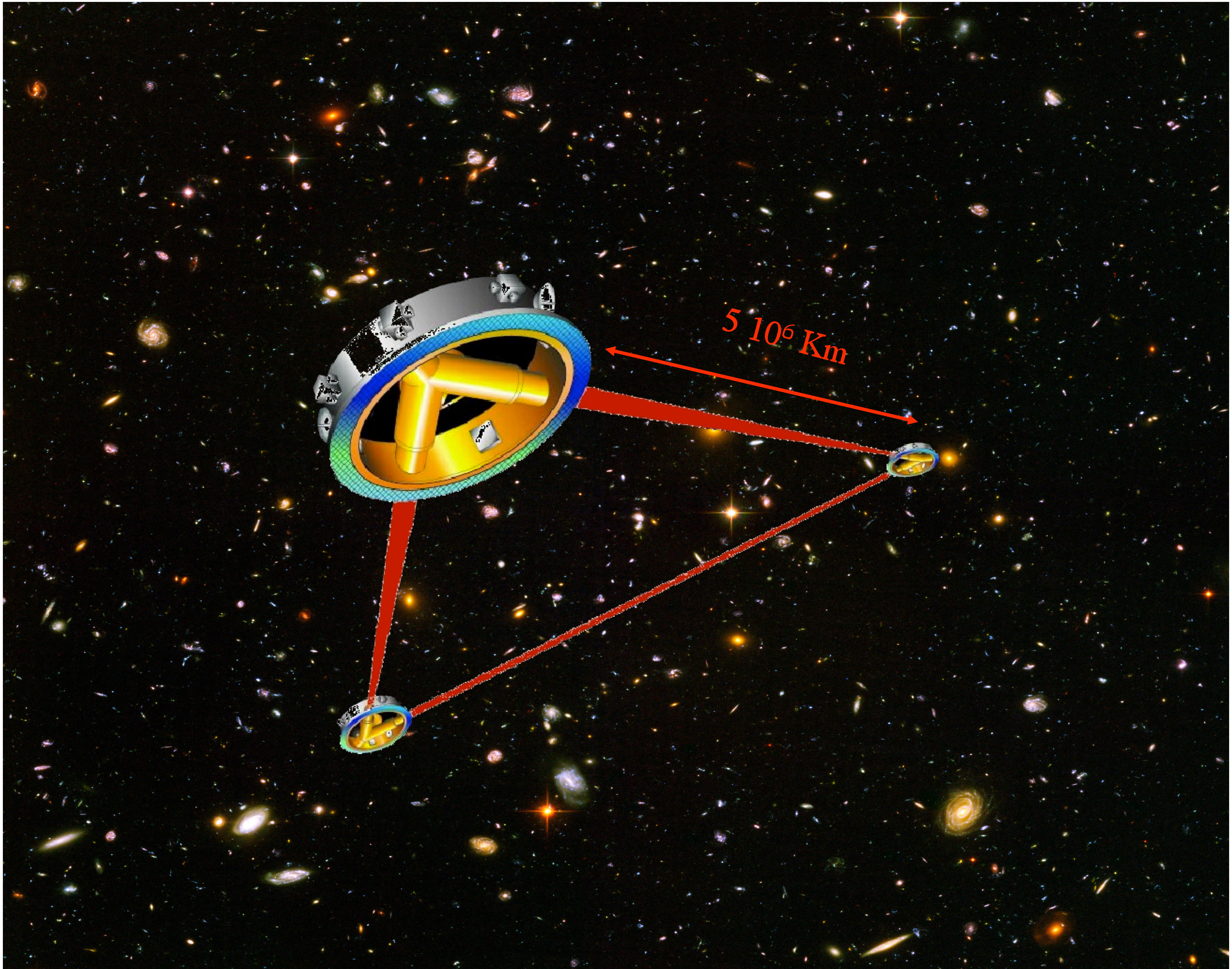
6×10^{9} times better than Michelson/Morley 1887!

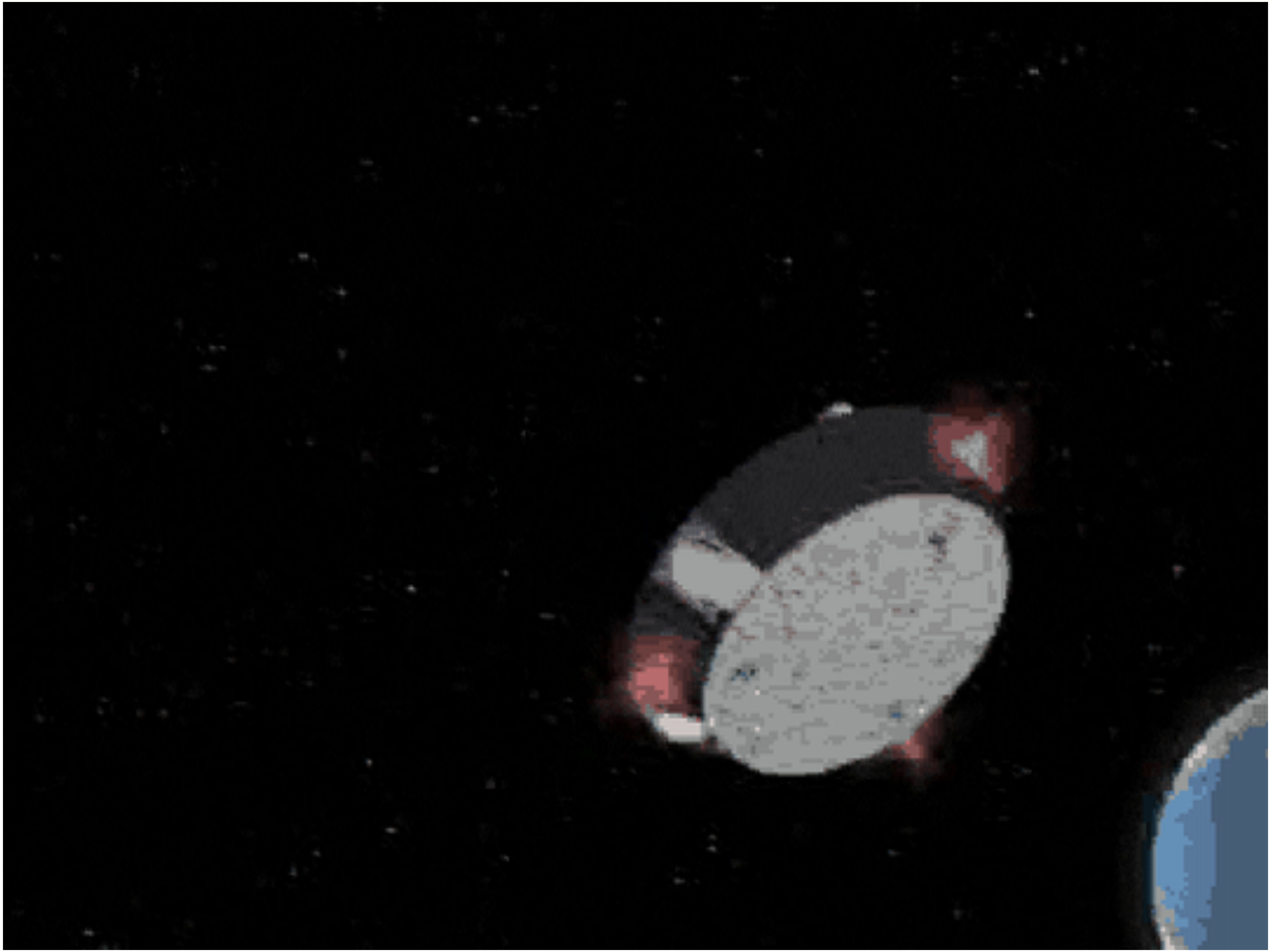
How to completely get away with the seismic wall?



Go into space : LISA interferometer




5 10⁶ Km



That's all for today!

Outline

1. An extraterrestrial radiation
2. The light of particles
3. Detector Earth
4. Ripples of spacetime

EXTRA

1. Particle detectors in space
2. Going underground: neutrinos and dark matter

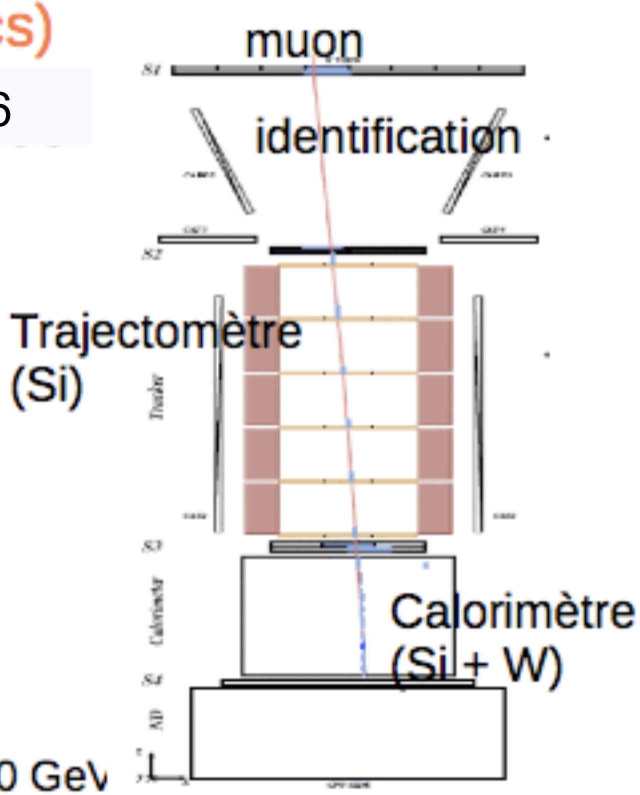
4. Particle detectors in space

Why go into space?

Catch the primary cosmic particles before they hit the atmosphere and form cosmic ray showers.

PAMELA (Payload for AntiMatter Exploration and Light-nuclei Astrophysics)

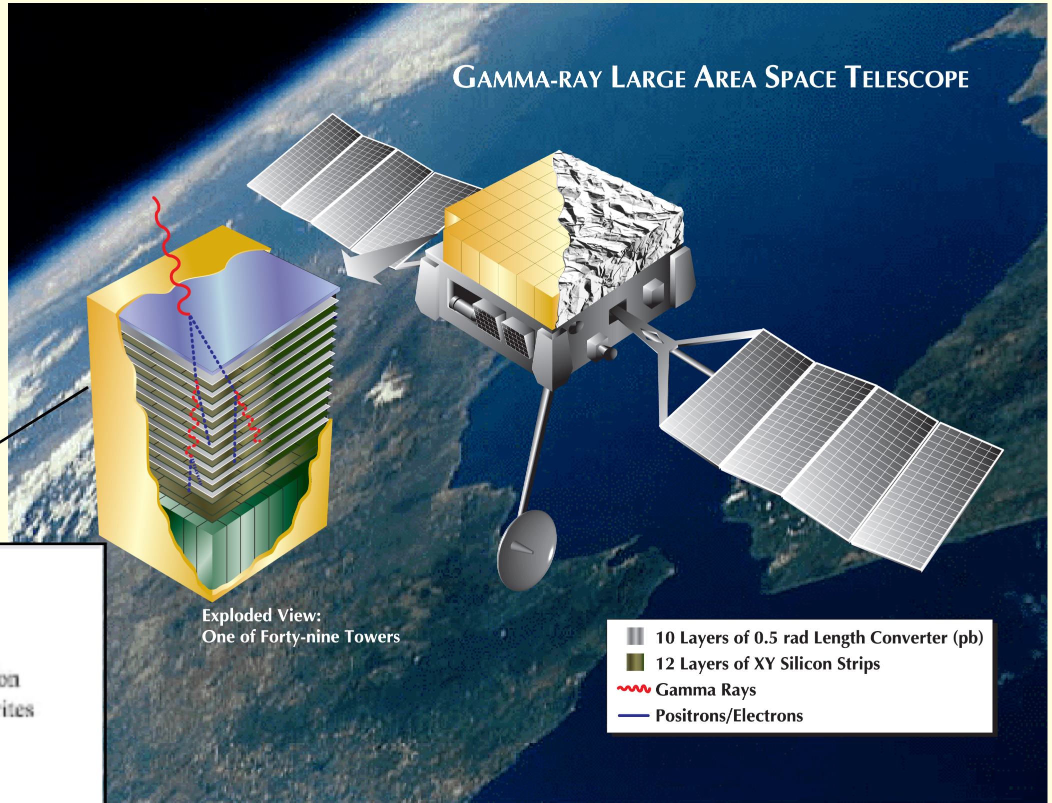
launched in 2006



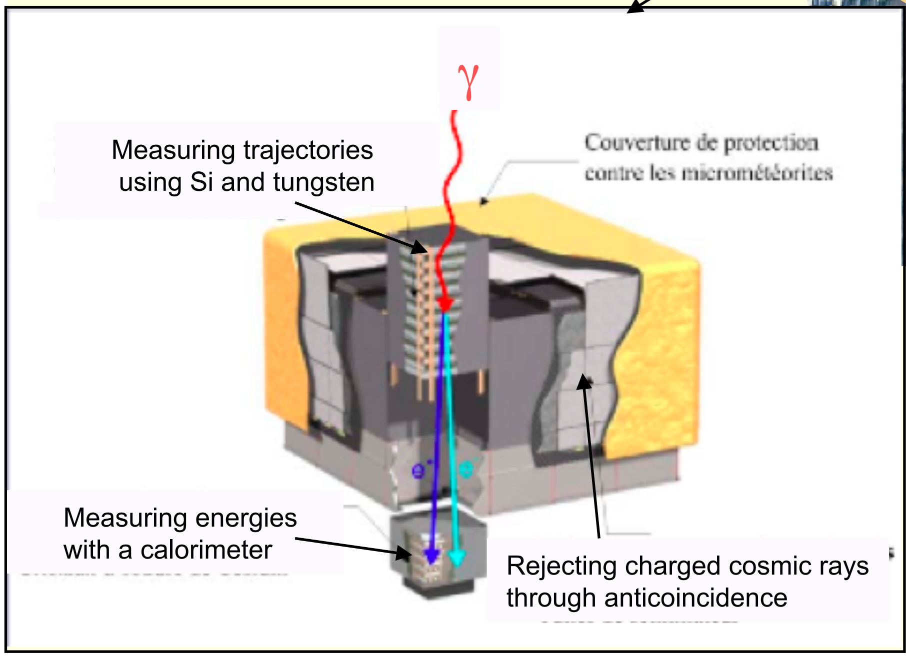
antiprotons (80 MeV–190 GeV
positrons (50 MeV–270 GeV).

Launch in 2008

γ from 10 keV to 300 GeV

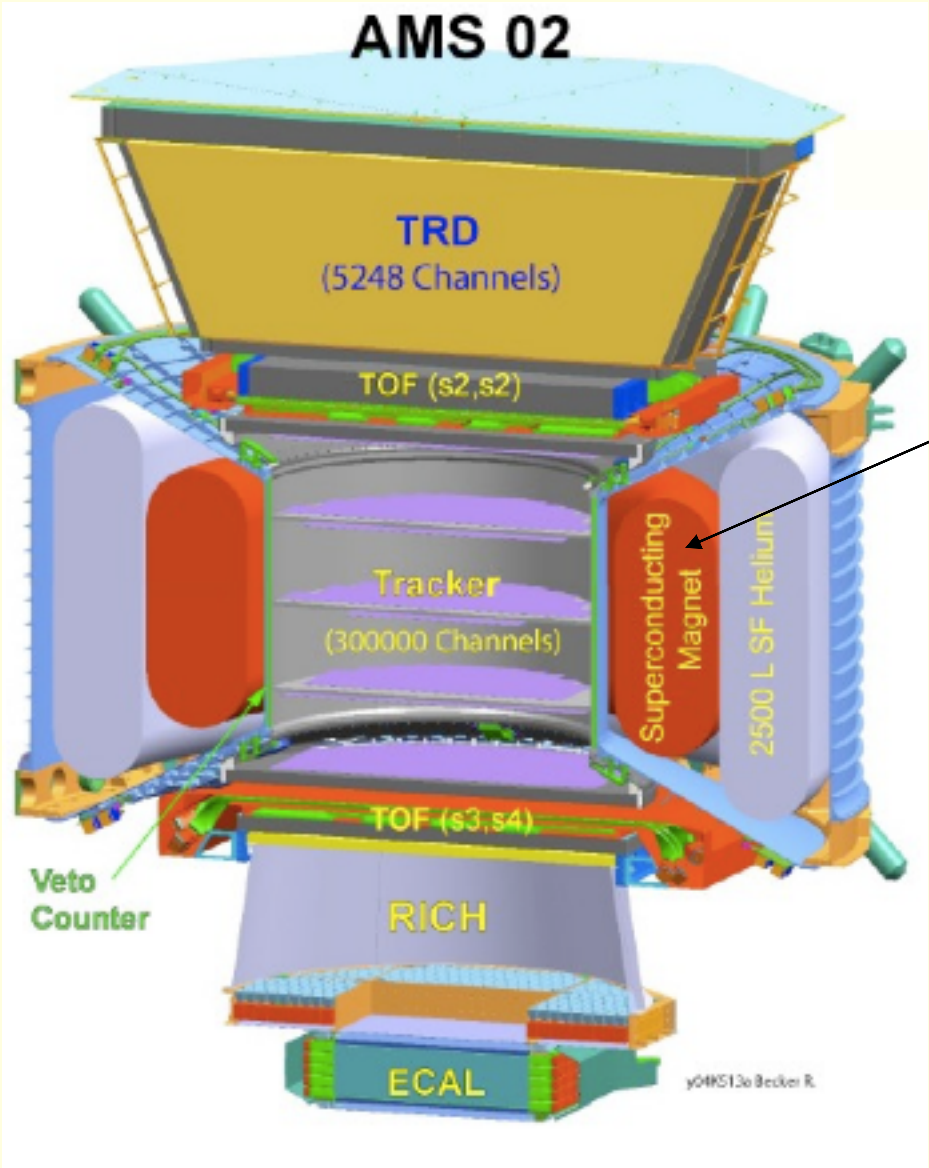


Large Area Telescope (20 to 300 MeV)



Detecting the primary particles responsible for cosmic rays: AMS on the ISS

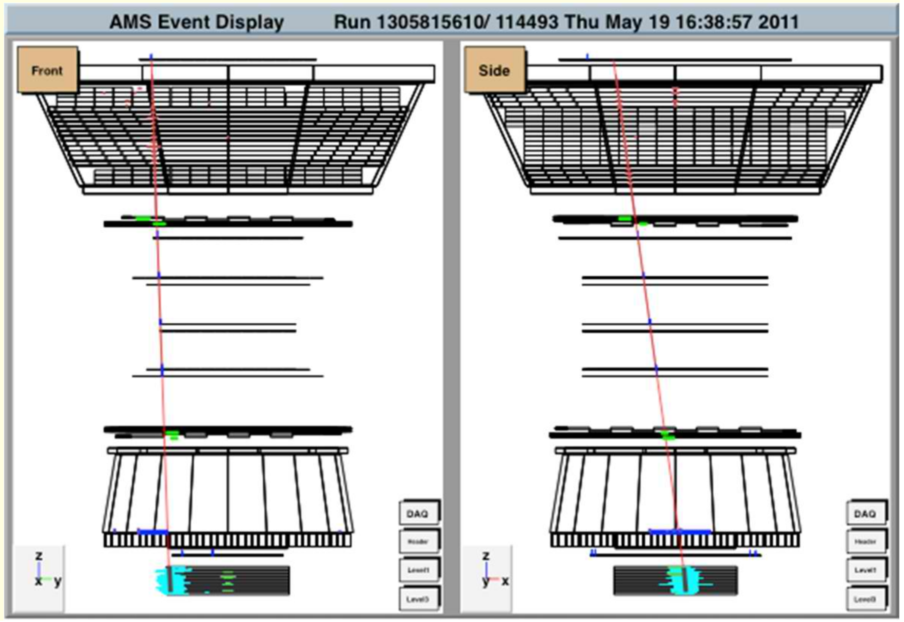
(launch 16 May 2011)



permanent magnet
(charged particles)

AMS02 anchored on the ISS

20 GeV electron   42 GeV carbon

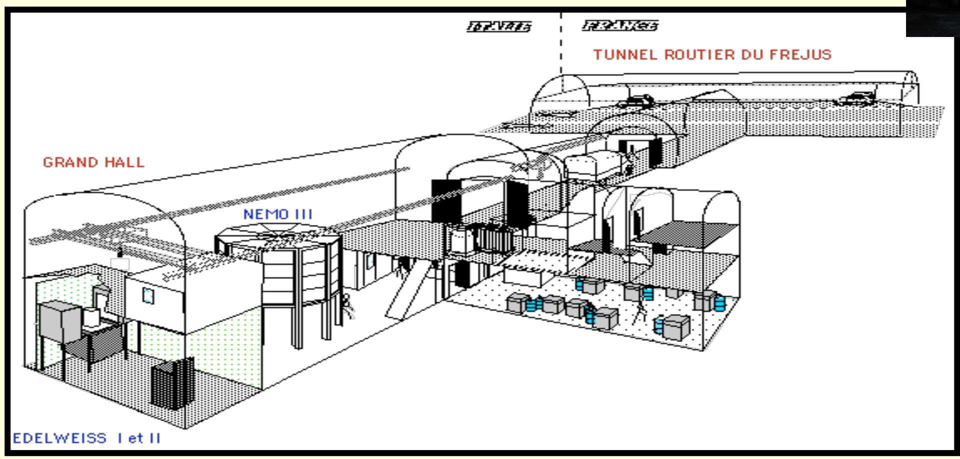


First events collected on 19 May 2011

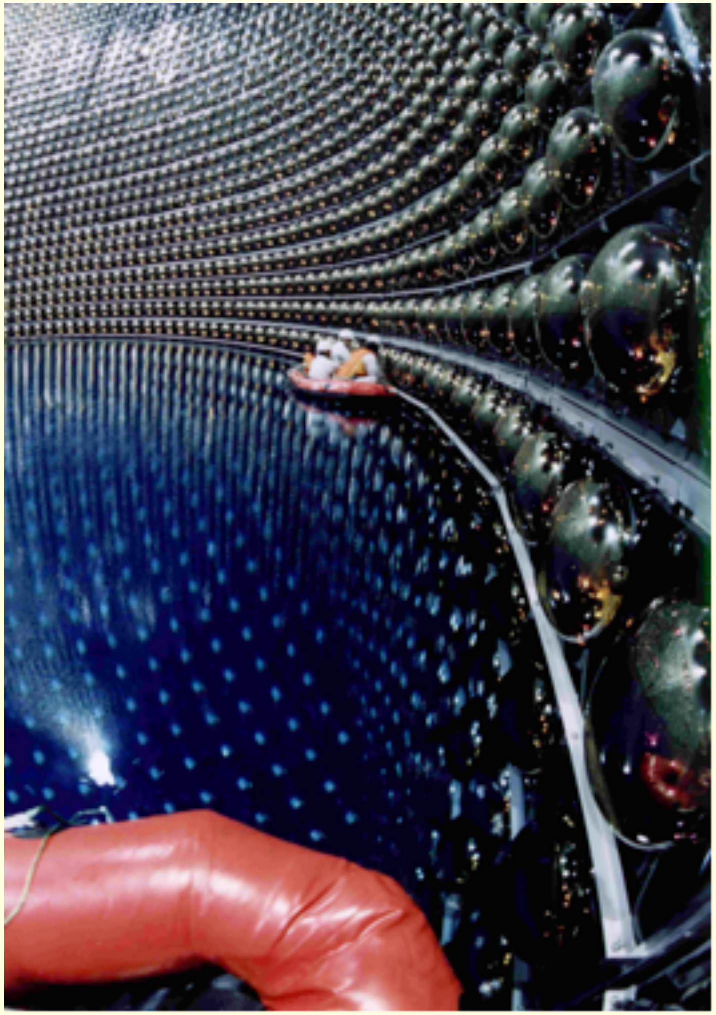
5. Going underground

The detection of elusive particles such as neutrinos or dark matter particles requires very low background environments, hence to hide from cosmic rays

→ underground laboratories



Neutrino (solar and atmospheric) detectors



SuperKamiokande (in Japan) during the filling of the tank

Edelweiss-II experiment to detect dark matter